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NUCLEAR WEAPONS EFFECTS IN A FOREST ENVIRONMENT—THERMAL AND FIRE

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ABSTRACT

This handbook describes nuclear weapon thermal output and its effects on forest and wildland environments. Specific topics include a description of the nuclear thermal pulse and its transmission through the atmosphere for surface, atmospheric, and high-altitude bursts; ignition requirements of alpha cellulose and wildland fuels (including living vegetation); the classification and distribution of different types of forest fuels and climates and a discussion of fire potential; the behavior of single, multiple, and mass fires and firestorms; the post-fire environment; fire-fighting and evacuation methods; effects on military operations and man.

Also included for completeness are non-thermal effects on the forest and wildland — nuclear radiation and air blast effects — together with synergistic considerations, such as blast-fire and fire-fallout interactions.

CHAPTER 1
INTRODUCTION

1.1 SCOPE

This handbook describes the basic thermal effects associated with nuclear weapons, applies them to selected forest and wildland environs typical of a range of climates and geographic locales, relates thermal effects (fire in particular) to other weapons effects, and provides guidance to organizations and individuals involved in operations in forested and other wildland areas that may be subjected to nuclear weapons effects. Throughout the book, the term "forest" is used to represent all wildland environments except where otherwise specified.

1.2 OBJECTIVES

- To provide a basic source book of information on thermal effects, principally fires in forests and other wildland areas, complementing publications that discuss other nuclear detonation effects.
- To provide a basic source book of information on forest types and on geographical, topographical, and meteorological factors significant to the evaluation of thermal and fire problems for forested areas.
- To provide data and methods for interrelating forest factors and all relevant nuclear weapons effects parameters.
- To provide guidance to commanders, operations planners, and individuals, in order to facilitate survival and operational success in a forest fire environment. While oriented largely toward military units and nuclear weapons, in many respects the guidance is applicable to civilian groups and non-military fire situations.

1.3 GENERAL

Thermal effects are interrelated with other effects, with operations, and with the environment in a complex but partially quantifiable fashion. This handbook summarizes current knowledge of significant factors. The following paragraphs set forth important topics covered in the texts.

There is major interaction between thermal and blast effects caused by blast rearrangement of fuels and wind effects on ignitions. There is noticeable interaction between nuclear fallout and fires because fire updrafts modify fallout deposition patterns and redeposit fallout already on the ground.

Operationally, the presence of fallout in a fire area can increase casualties both directly and by inhibiting fire-control or evasion activities. In addition, operationally, a forest fire tends to inhibit movement, interfere with visual and electronic surveillance, increase materiel and personnel casualties, remove concealing foliage, and divert resources.

As well as providing concealment, foliage may intercept a significant fraction of the incident thermal pulse, thereby reducing both initial burns of personnel and materiel and the number of primary ignitions.

The extent of the area initially ignited, the rate and extent of fire spread, and the number and severity of initial casualties, depend critically on the season of the year, weather conditions at the time of weapon detonation and for some weeks beforehand, and the general character and vigor of the vegetation.

The rate and extent of fire spread and the feasibility of evading, suppressing,or limiting the fire depend heavily on forest type, ground fuel, topography, and the presence of natural barriers.

1.4 ACTION REQUESTED

It is incumbent that commanders and planners operating in a forest environment under conditions of nuclear war take note of not only the threat posed by initial weapons effects, but also the fire environment. Forest fires add a new dimension to the problem of avoiding bottlenecks and otherwise complicate the planning problem.

Implications for training may be derived from the planning factors just cited. Individual survival training is also required. Finally, the post-fire environment must not be neglected. Even after fires are out the nature of the zone of operations is far different from its pre-fire condition and may be even more unmanageable than during the burn period.

CHAPTER 2

NUCLEAR THERMAL PULSE

2.1 INTRODUCTORY COMMENTS

In evaluating the incendiary and other damaging thermal effects of nuclear detonations, it is not sufficient to know only the total thermal energy incident on the target area. Several other fairly important factors also must be specified. These include the time-irradiance history (the "pulse") of the thermal exposure, its spectral distribution, and its angular incidence on target surfaces. These factors are determined by the nature of the detonation, its total energy yield, its height of burst, and its immediate environment; however, they are also modified by the atmosphere between the burst and the target elements. Moreover, the response of the target to the incident radiation is characteristic of the nature of the component parts of the target and of its own environment both currently and, in some cases, its recent past history. This chapter deals with the thermal characteristics of the nuclear pulse and their dependence on the conditions of burst without regard for the surrounding atmosphere.

2.2 THE NUCLEAR FIRE BALL

Immediately following the initiation of the nuclear reactions in the core of the nuclear weapon, in a very brief fraction of a second before enough time has passed for the outward motion of expanding core material to have any effect on the bomb case, X rays begin streaming out into the surrounding environment. These X rays result from the extremely high temperatures existing in the bomb core (tens of millions of degrees - about 1 keV) and may represent as much as three quarters of the total energy release of the nuclear reaction.

The nature of this radiation, its spectrum, and the amount of it that escapes the weapon to interact with the environment is determined by the construction of the weapon rather than by the environment. Despite this, the thermal radiation which eventually reaches a distant target, in most circumstances, is largely independent of the construction of the weapon. The thermal radiation is determined primarily by the environment in which the detonation occurs.

This document is concerned principally with detonations in air, i.e., atmospheric bursts ranging from surface bursts and sea level altitudes to high altitude bursts which are generally a few hundred thousand feet or below. In air the soft X rays that escape the weapon case are absorbed by the air surrounding the point of detonation and heat that air to very high temperatures. The growth and development of the fireball is a very complex process which is not of concern here. It is sufficient for purposes herein to state that the heated air making up the fireball radiates very large amounts of energy to its surroundings in the visible and near-infrared portions of the spectrum, i.e., the main thermal-radiation pulse. Under most circumstances this radiation is determined by the characteristics of the air and therefore the spectral distribution of the radiation is, for all practical purposes, the same for all detonations in air. The size of the fireball is determined by the total energy release of the detonation and by the density of the air surrounding it. As a rough rule of thumb, about one kiloton of air is heated to make up the fireball for every kiloton of energy release. Accordingly, the volume of air making up the fireball increases in direct proportion to the energy yield of the detonation (its radius in proportion to the cube root of the yield) and its dimensions increase with altitude. The amount of the thermal radiation energy emitted and the duration of the thermal radiation pulse are also determined by the total energy yield of the weapon and burst altitude. The effective thermal radiation yield is a large, nearly constant fraction of the total yield (about one-third to one-half), except for contact surface bursts and to a lesser extent for air bursts whose fireballs interact with the surface, and bursts at such great altitude that for all practical purposes they are above the atmosphere. For the exceptions mentioned above, the fraction is always somewhat smaller and at extremely high altitudes will range down to insignificant values.

For low altitude bursts the thermal radiation pulse lasts from about a second or two for weapons in the nominal-yield category to tens of seconds for weapons in the lower megaton-yield range and may last as long as a minute or more for the very largest weapons.

Strictly speaking, there is no instant in time that marks the end of the thermal radiation from the detonation. At late times, as the residual fireball and its cloud of radioactive debris rise, the heated air in this cloud is still radiating some thermal energy; however, this radiant energy is released so slowly that it has little military importance. Therefore, in this handbook, the terms "thermal radiation phenomena," "thermal effects," and "thermal pulse" only pertain to that portion of the radiated energy which more accurately could be termed the prompt thermal pulse. This restriction in the meaning of terms such as "thermal effects" excludes a number of nuclear burst phenomena that are really thermal in nature. For example, fireball rise is a thermal effect in the broad sense of the term; the fireball is buoyant for the same reason that a hot air balloon is buoyant. These effects, however, are not germane to our subject.

2.3 DEPENDENCE OF FIREBALL SIZE AND THERMAL EMISSION ON THE CONDITIONS OF BURST

The size of the fireball and the characteristics of the thermal pulse are both important factors in determining the damage effectiveness of a nuclear detonation. They depend not only on yield and altitude, but also on interactions with the ground. This section will describe several of the more important cases. The simplest of these cases is the low altitude air burst. The other cases are basically modifications of this case.

2.3.1 Low Altitude Air Bursts (less than about 100 kft)

The thermal radiation pulse from a low altitude air burst exhibits the characteristics shown in Figure 2-1. The total thermal energy radiated by the detonation, E, is just the radiant power, P, integrated over the total duration of the pulse ($E = \int_0^\infty Pdt$). The time scale in Figure 2-1 is normalized to the time of maximum radiant power emission t_{max}, to make the figure generally applicable to all yields. Values of t_{max} increase with yield, W, approximately as $W^{0.5}$. A 20-KT low altitude air burst has a t_{max} of about 150 milliseconds, so an approximate scaling relationship for t_{max} is $0.032\ W^{0.5}$ for W in kilotons. In spite of its limited accuracy, this equation has the advantage of convenience in that if it is converted to megaton units, it becomes $t_{max} \approx W^{0.5}$. Within the range of about 1 KT to several megatons, this equation is good for low altitude air bursts to about ±30 percent.

At altitudes above sea level, t_{max} is also proportional to the square root of atmospheric density so that $t_{max} = (W\ \rho/\rho_0)^{0.5}$, where ρ is atmospheric density at altitude, and ρ_0 is the density at sea level. Since the density of 20 miles altitude is about one-hundredth of that

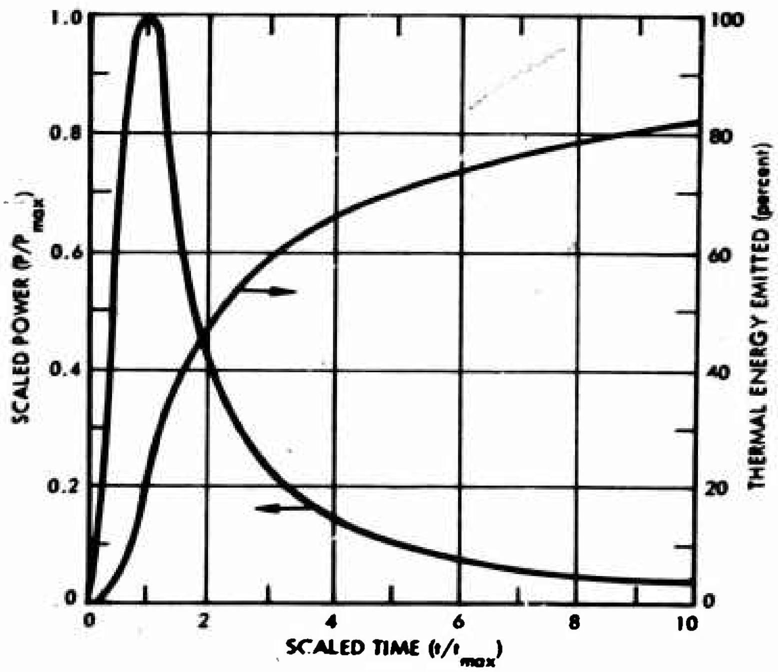

Figure 2-1. Scaled fireball power and fraction of thermal energy versus scaled time in second thermal pulse of an air burst (Reference 1).

at sea level, the thermal pulse from an explosion at that altitude is about an order of magnitude shorter duration than at sea level. As a convenient rule it can be stated that atmospheric density changes by roughly a factor of 10 for every 10 miles of altitude. These facts are summarized in Figure 2-2 showing pulse durations for various weapon yields at various altitudes, using appropriate exponents just discussed.

The fireball radius at t_{max} can be similarly scaled with yield. For near sea level air bursts, the radius is given approximately (within ± 30 percent): by R_{max} (in feet) $\simeq$ 180 $W^{0.4}$ for W in KT. Figure 2-3 illustrates the change in fireball radius with yield for a variety of burst altitudes, using the appropriate exponent.

2.3.2 Surface Bursts

When a nuclear explosion occurs on or near the surface of the earth, the explosion phenomena are affected in several ways. Provided the distance above the surface is not great compared to the fireball dimensions, the phenomena are essentially the same as for the bursts occurring on the surface. As the height of burst increases

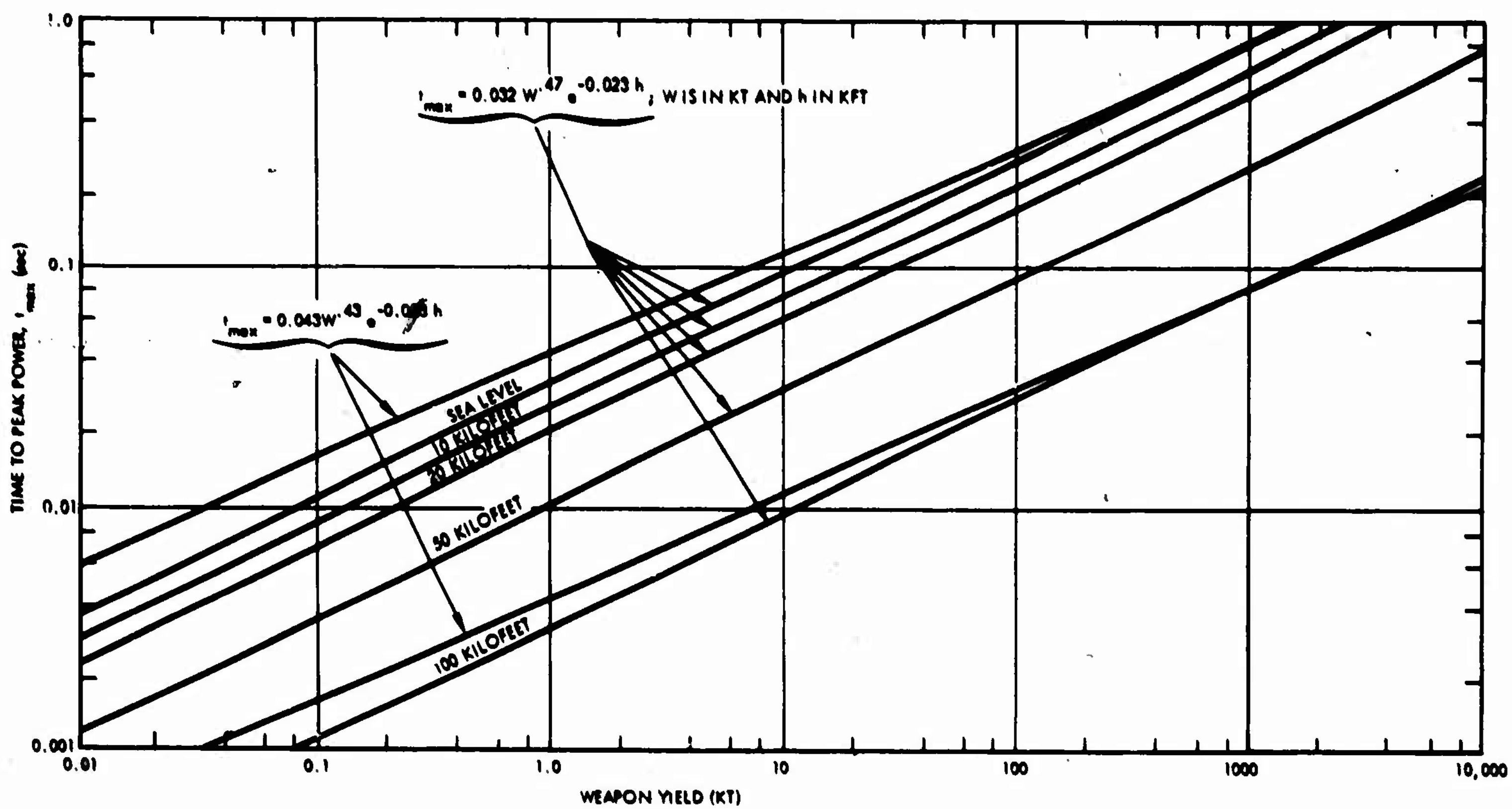

Figure 2-2. Yield vs. time to peak power.

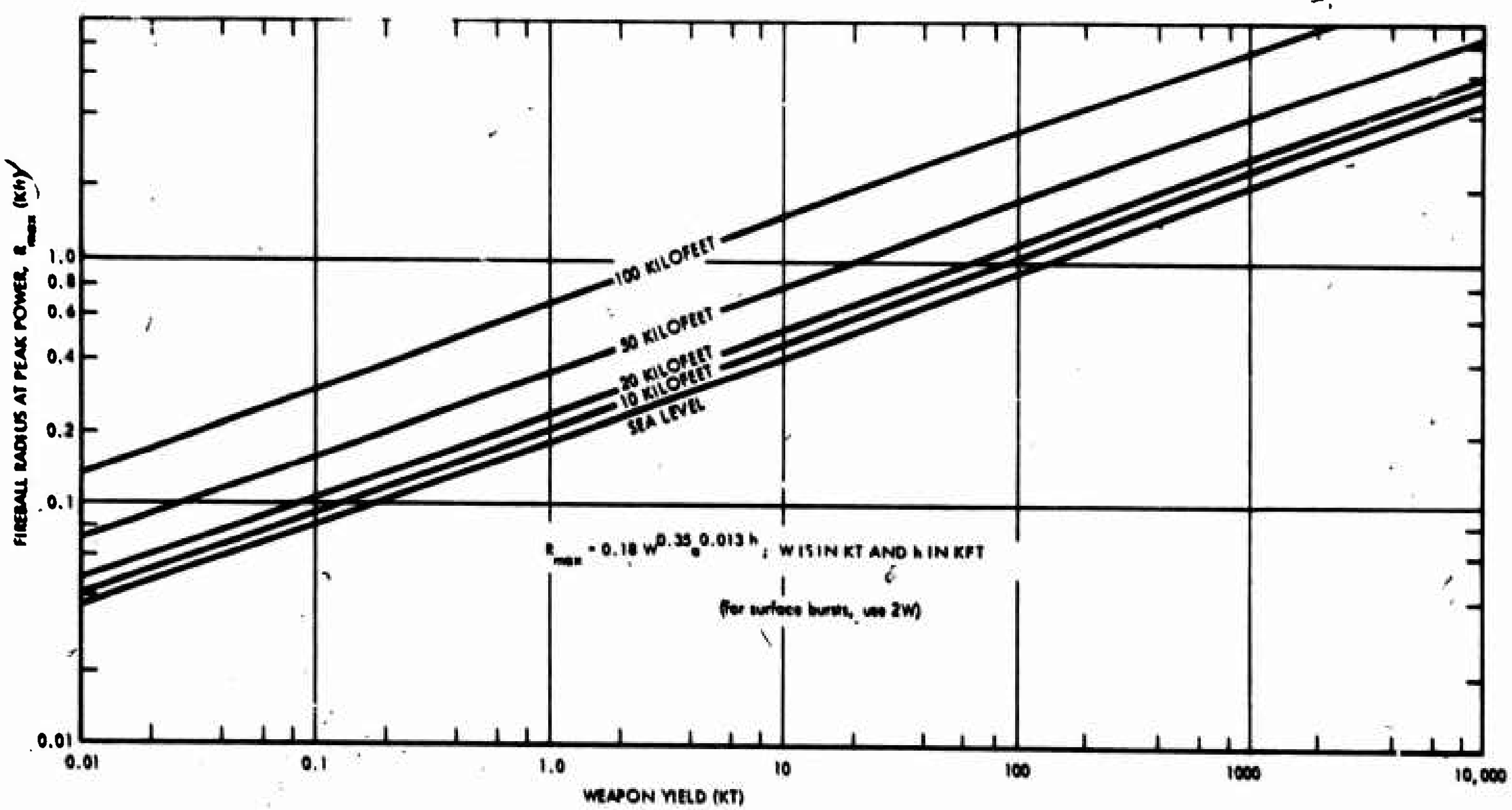

Figure 2-3. Yield vs. fireball radius.

up to a point where the fireball, at its maximum size, no longer touches the land or water, there is a transition zone in which the behavior is intermediate between that of a contact surface burst and an air burst.

In a surface or near-surface burst, the fireball in its initial rapid growth will touch the surface of the earth and a significant fraction of the X rays will be absorbed by the surface material. Because of the intense heat, a considerable amount of rock, soil, water, and other material located in the area will be vaporized and taken into the fireball, reducing its temperature. The proportion of the explosion energy appearing at a distance as thermal radiation will be less than for an air burst. Some energy is utilized in melting or evaporating surface material, but this is relatively small (about 1 to 2 percent) and has a minor effect on the thermal radiation emitted. As far as the energy received at a distance from the explosion is concerned, other factors are more significant. First, there will be a certain amount of shielding due to terrain irregularities and second, some absorption of the radiation will occur in the dust or water vapor produced near the burst point in the early stages of the explosion.

Both the pulse duration and the dimensions of the fireball are increased by interaction with the surface. In fact, the fireball for a surface burst of a weapon of yield W develops approximately as that of an air burst of yield 2W. Estimates of pulse duration and fireball radius for surface bursts are available from Figures 2-2 and 2-3 by using 2W in place of W.

2.3.3 High Altitude Detonations

Below about 100,000-foot-altitude the pulse shape previously described for low altitude detonations is reasonably accurate and the scaling laws for low altitude air bursts apply. Above this altitude the thermal pulse becomes significantly distorted and the distortion progresses with increasing altitude. Also with increasing altitude the fraction of yield appearing as blast is progressively reduced, a large fraction of the thermal energy is emitted at very early times, and the effective duration of the pulse is increasingly curtailed. In spite of these changes, the previously discussed scaling relationships adequately apply for most purposes of estimating incendiary and other thermal responses on the ground.

2.3.4 Very High Altitude Detonations

At very high altitudes (greater than 50 miles) the fireball will tend to be distorted by the atmospheric density gradient, becoming flattened at the bottom and elongated at the top. If the burst altitude is increased sufficiently, the X rays emitted upward will escape the atmosphere completely and only those emitted downward will be absorbed when they reach denser air. Therefore the fireball tends to assume the shape of a pancake or very shallow cone centered at an altitude that depends on the X-ray energy but not on the actual burst height. For a bomb temperature of about 1 keV, this altitude is about 50 miles. The radius of the heated layer is approximately h-50 miles; h is the weapon-burst height.

The period during the first few milliseconds of the thermal pulse from a detonation at these heights contains 10 to 20 percent of the energy deposited in the air layer while the tail of the pulse, containing 20 to 50 percent of the energy, may last an additional .1 to 100 seconds, depending on burst height, yield, and bomb temperature, with the values of lesser radiating efficiency considered more likely. The rate at which absorbed energy is re-emitted from the fireball and the effective fireball radiating temperature are functions of its initial temperature and density, which can vary widely depending on these burst parameters. Note that here is a case where weapon design, specifically, yield-to-mass ratio, can have a considerable influence on fireball behavior, since the altitude and density of the fireball layer are dependent on the initial bomb temperature.

It is very unlikely that detonations at such great height would ever be used on wildland targets because of their inherent lack of damaging effectiveness for ground targets. Should such detonations occur over wildlands for other reasons such as the result of IBM intercept, the likelihood that they could start fires on the ground is considered to be small, but there are insufficient data from weapons tests for firm conclusions to be reached.

2.4 REFERENCE

1. Glasstone, S. ed., The Effects of Nuclear Weapons, Department of Defense, U.S. Government Printing Office, Washington, D.C., Revised Edition, 1964.

CHAPTER 3

THERMAL TRANSMISSION

3.1 RADIANT EXPOSURE OF DISTANT TARGET

In the absence of atmospheric attenuation, the divergence of the thermal energy as it propagates away from the fireball causes the radiant power per unit area (called the radiant exposure), denoted as Q, to decrease as the inverse square of the distance. At a distance D from the fireball, the thermal energy is distributed over a spherical area of $4\pi D^2$. Since the total thermal energy emitted by the fireball, $E \approx fW$ (KT) $= fW \times 10^{12}$ (in calories) is uniformly distributed over such a spherical surface, the radiant exposure at a distance, neglecting atmospheric attenuation, is $Q = fW \times 10^{12}/4\pi D^2$ (in calories per unit area) where f is the fraction of the total yield in the form of thermal radiation energy. If the distance is given in units of centimeters the radiant exposure has units of calories per square centimeter. Kilofeet, kilometers, and miles are more convenient units than centimeters for measuring the range from a nuclear burst. Appropriate conversion factors allow us to retain the units of cal cm^{-2} sec^{-1} for Q while putting D in more convenient units; e.g., $Q = 7.96\ fW/D^2$, for D in kilometers; and $Q = 85.7\ fW/D^2$, for D in kilofeet. If D is expressed in miles, $A \simeq W/D^2$ (assuming $f = 1/3$). This is the basis for the popular rule of thumb: for each KT of yield, a radiant exposure of 1 calorie per square centimeter will be delivered at one mile.

The rate at which the radiant exposure is delivered to the target is called the irradiance, H, and bears the same relationship to the total thermal power, P, as radiant exposure, Q, does to total thermal energy, E. Therefore, the scaled-time relationship of total radiant power and energy shown in Figure 2-1 applies equally well to the analogous quantities dealing with exposure of a surface at any distance from the point of detonation.

The radiant exposure of a material will, in general, be less than that indicated above. If the exposed surface is not normal to the angle of the rays of the radiation, the radiant exposure will be reduced as the cosine of the angle. Any obscuring materials between the fireball and the target, including microscopic particles in the air, will reduce the radiant exposure of the target. Opaque solid objects completely attenuate direct thermal radiation.

Air both scatters and absorbs thermal radiation, but for those wavelengths which are not absorbed relatively close to the fireball, air is primarily a scattering medium. At large distances the radiation "scattered" may be as large or larger than the direct radiation. In this case the shielding afforded by opaque materials in the line of sight may be significantly lessened.

Obviously a major factor in determining how much thermal radiation arrives at a distant surface is the transmission of the atmosphere. It is also a major source of uncertainty in current attempts to assess thermal effects. Methods for estimating the overall atmospheric transmittance (defined as that fraction of the thermal radiation which arrives at a distant point having traversed an intervening, scattering atmosphere), are discussed in the next section.

3.2 ATMOSPHERIC TRANSMISSION

Because of the nature of the atmosphere and because of the processes involved in atmospheric attenuation, it is important to consider two cases; (1) transmission through the atmosphere near the ground and (2) transmission from fireballs above the lower atmosphere.

3.2.1 Transmission Through the Lower Atmosphere

When the atmosphere is clear or hazy and cloudless, and when the fireball is near the surface, the radiant exposure level at the ground depends heavily on the attenuation properties of the atmosphere near the ground and is assessed with adequate precision from conventional estimates of visibilities along the ground. For large slant ranges (relative to the visual range), the transmittance falls off so rapidly with distance that the horizontal ranges for given radiant exposure levels do not increase substantially with increased weapon yield. This provides a point of diminishing returns in thermal effects.

Calculations of atmospheric transmission that require only information about along-the-ground visibilities, Figure 3-1, are probably of adequate reliability for distances of the order of the visual range,

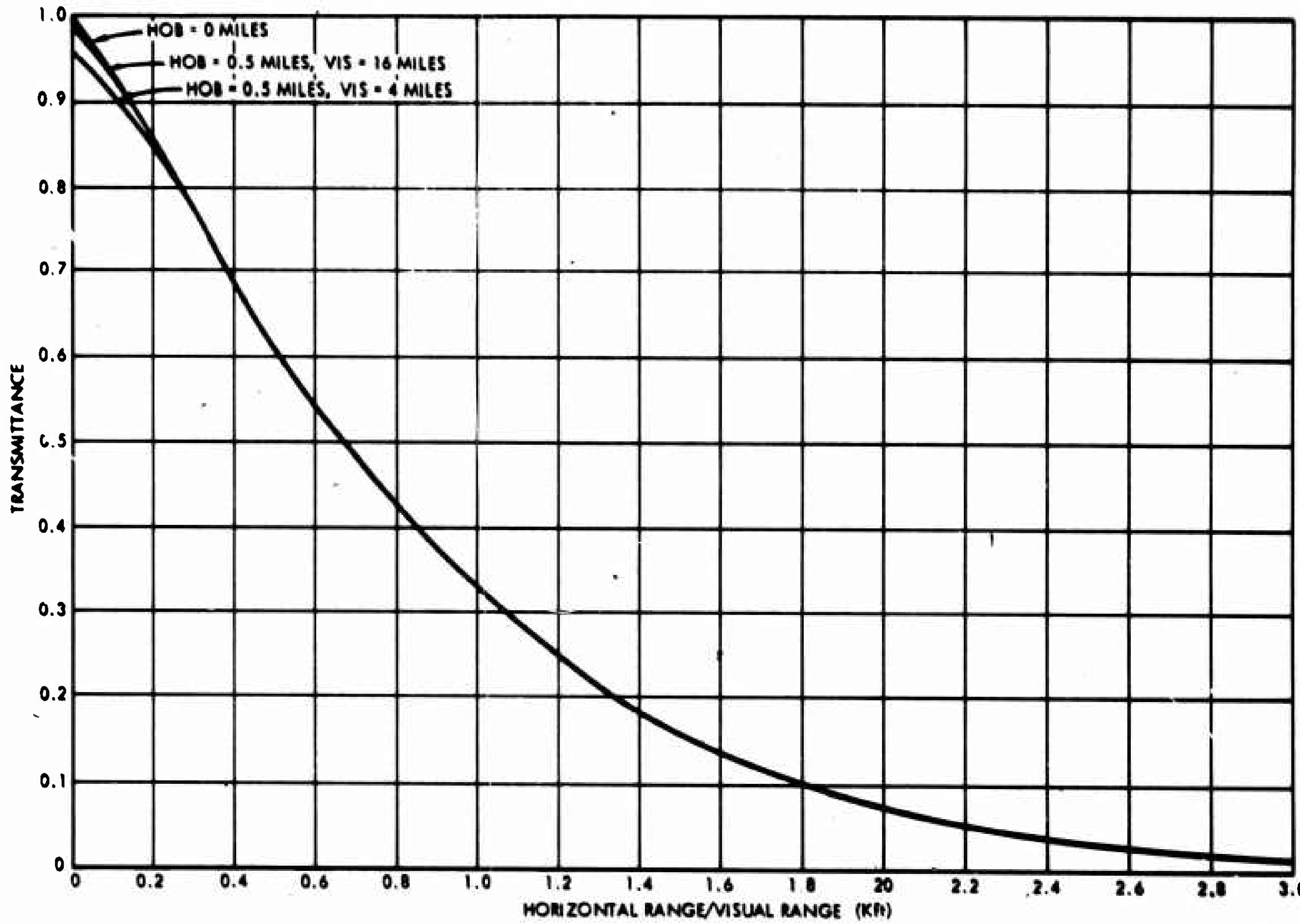

Figure 3-1. Atmospheric transmittance for sources in the surface haze layer expressed as a function of the visual range.

but their utility is limited to surface and near-surface airbursts and airbursts closer than about 2 kilofeet to the ground of weapons having yields less than about a megaton. The fireballs of megaton-class weapons are so large that even for surface bursts the transmission path for much of the radiation is at least partially above the surface haze layer. For such situations visibility is not a useful parameter for assessing atmospheric attenuation.

3.2.2 Transmission from Sources Above the Lower Atmosphere

For large-yield detonations and for any other situations where the fireball may be regarded as being above the scattering layer near the ground, atmospheric transmission values for cases of extremely clear and hazy conditions without clouds may be estimated with reasonable confidence from Figures 3-2 and 3-3.

Attenuating or reinforcing effects of clouds, together with the surface albedo, are applied as multiplicative factors to the foregoing values for cloudless atmospheres with low surface albedos to provide estimates of transmittance for complete atmospheres. These factors are listed in Table 3-1. In the same table visibilities are given for a variety of atmospheric descriptions as an aid in choosing visibilities when they are required but not known. For forest and other wildland areas surface albedos are generally low.

3.3 ESTIMATING FREE FIELD RADIANT EXPOSURES

From these facts, combined with those given in Chapter 2, it is possible to extend weapons test data to cover most of the situations of practical concern. Figures 3-4 and 3-5 provide a basis for estimating free-field radiant exposures on targets for low altitude air bursts. Note that in these figures radiant exposures are normalized to one kiloton. Values for surface bursts can be approximated by multiplying air burst values by ratios read from Figure 3-6. The situations illustrated are thought to be those of principle concern to operations in forests and other wildlands, i.e., surface bursts and low altitude air bursts.

3.4 OBSCURATION AFFORDED BY FOLIAGE AND STEMS

Before we can reliably assess incendiary effects or thermal injury to exposed personnel, we must evaluate the extent to which free-field radiant exposures can be modified by the attenuating components of

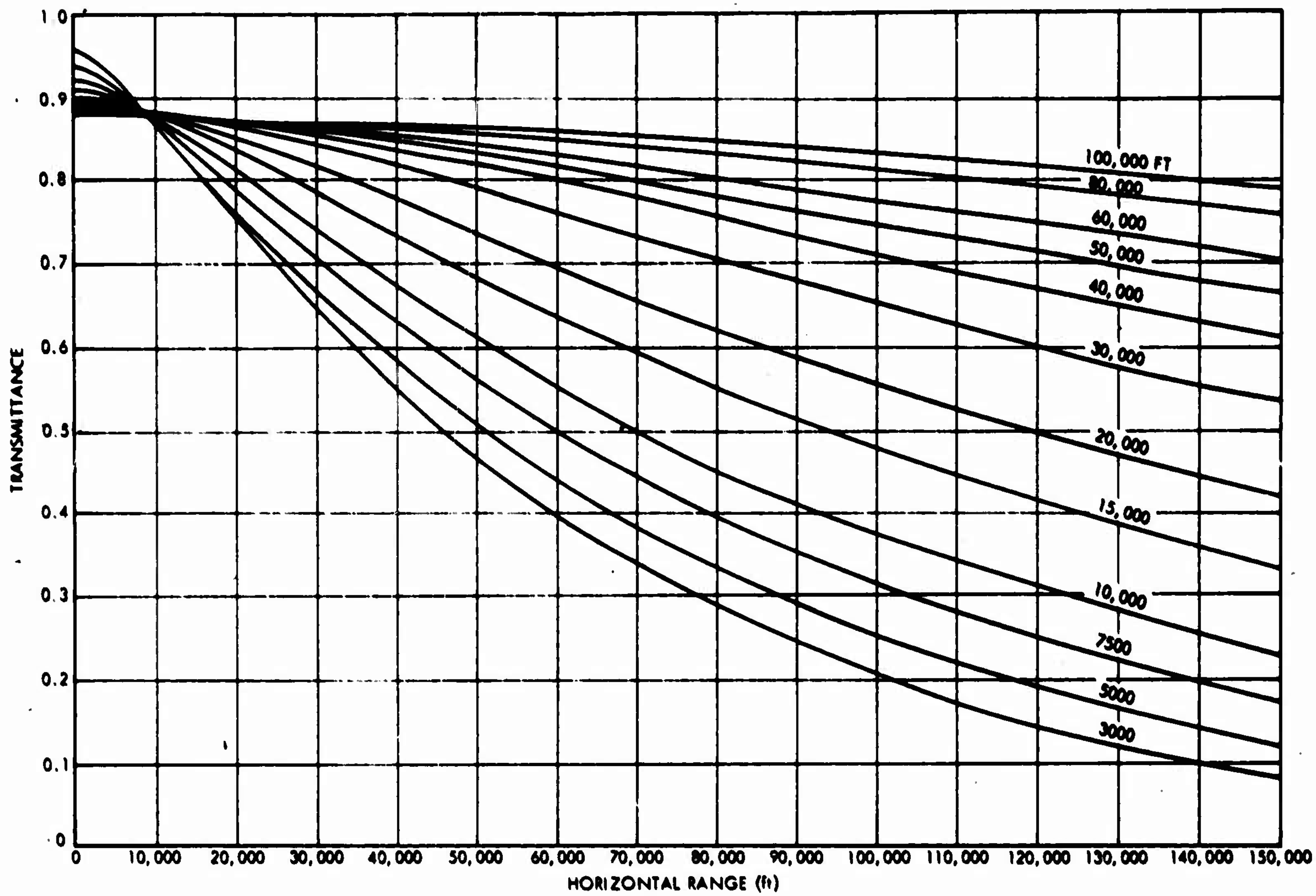

Figure 3-2. Atmospheric transmittance for sources above the surface haze (6.7 miles visual range). Curves represent different burst heights.

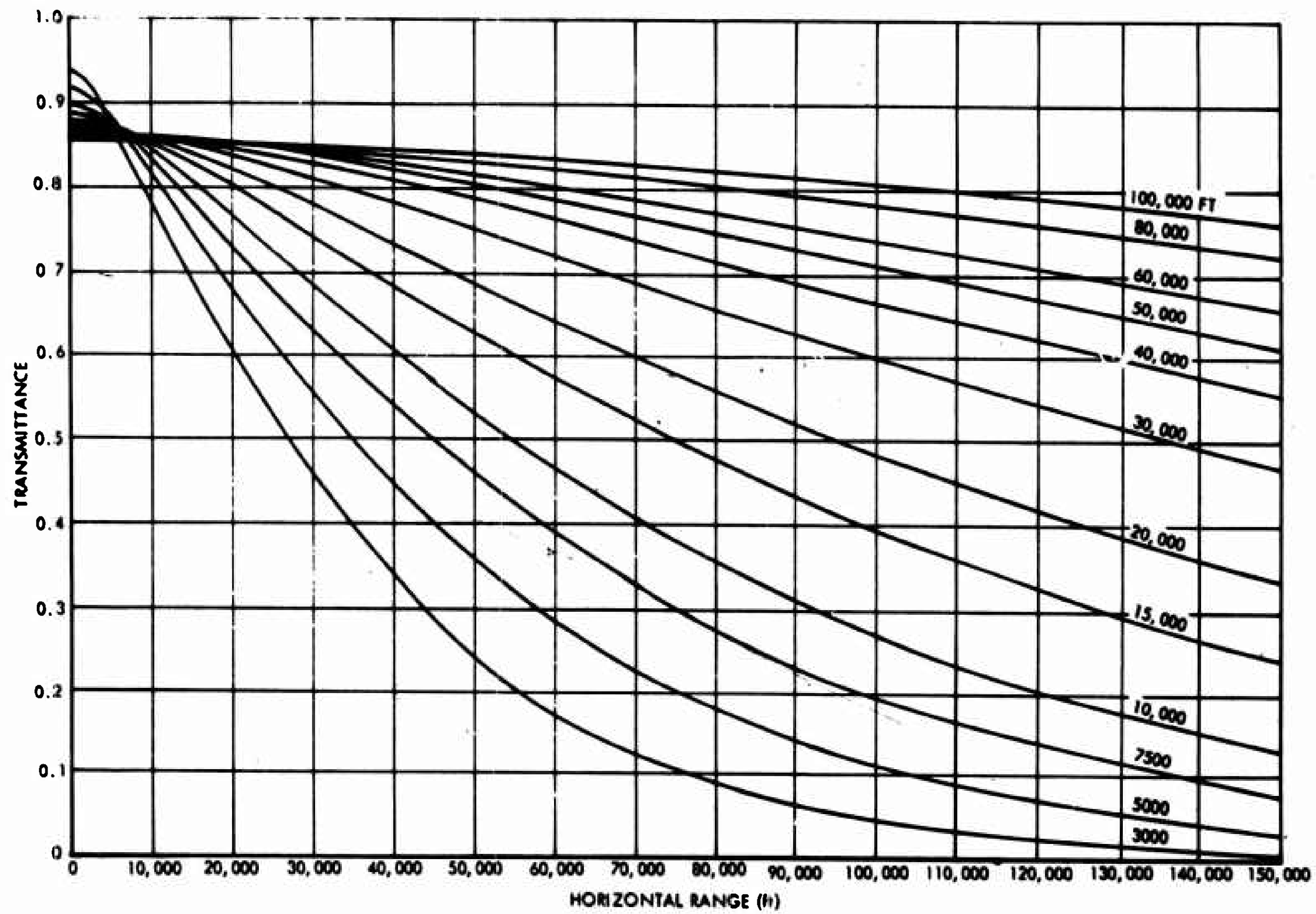

Figure 3-3. Transmittance for sources above the surface haze (20 miles visual range). Curves represent different burst heights.

Table 3-1. Modifying factors for transmission under various atmospheric conditions with high or low surface albedos.

Atmospheric Classification and Description				Transmission Modifying Factor[a]	
Surface[b]		Overhead		Low Surface Albedo	High Surface Albedo
Type	Visibility (mi)	Type	Description		
Very Clear	30	—	—	1.0	1.5
Clear	12	Clear	Sky, quite blue. Shadows, distinct, and dark.	1.0	1.5
Light Haze	6	Light Haze	Sky, white. Dazzling near sun. Shadows, visible, and gray.	0.7	1.05
Medium Haze	3	Medium Haze	Sky bright grayish-white. View sun without discomfort. Shadows visible but faint.	0.5	0.75
Heavy Haze	2	Heavy Haze	Sky dull gray-white. Sun's disc just visible. Shadows barely discernible.	0.4	0.6
Thin Fog	1.2	Light Cloud	Sky light gray with maximum luminance around sun. Sun's disc not visible, no shadows.	0.3	0.45
Light Fog	0.6	Medium Cloud	Sky dull gray with maximum luminance at zenith.	0.2	0.3
Medium to Thick Fog	<0.5	Heavy Cloud	Sky dark gray, gloomy.	0.1	0.15

[a]Transmission values, calculated for the case of a clear standard atmosphere (no clouds, minimal haze component, low surface albedo), are multiplied by the appropriate factor to provide estimates of transmission through clouded or hazy atmospheres over surfaces of either high or low albedos.

[b]The classification of haze or cloud layers on the ground used here is basically that given in the 1962 issue of "The Effects of Nuclear Weapons" by Samuel Glasstone (Reference 1). In attempting to make this list of conditions compatible with the accompanying list of conditions for overhead haze and cloud layers, two additional conditions have been included. Haze (2.5 mile visibility) has been subcategorized as medium and heavy haze with the visibility values taken arbitrarily as the nearest whole number above and below, respectively. Also light to thick fog (visibility of 0.5 mile or less) has been divided into light fog and medium to thick fog. Haze layers are described in the same subjective terms whether overhead or on the ground. A cloud on the ground, however, is termed fog. A light cloud on the ground is described as a thin fog on the basis of subjective visual judgment. Similarly a medium cloud layer on the ground appears as a light fog and a heavy cloud layer as a medium to thick fog.

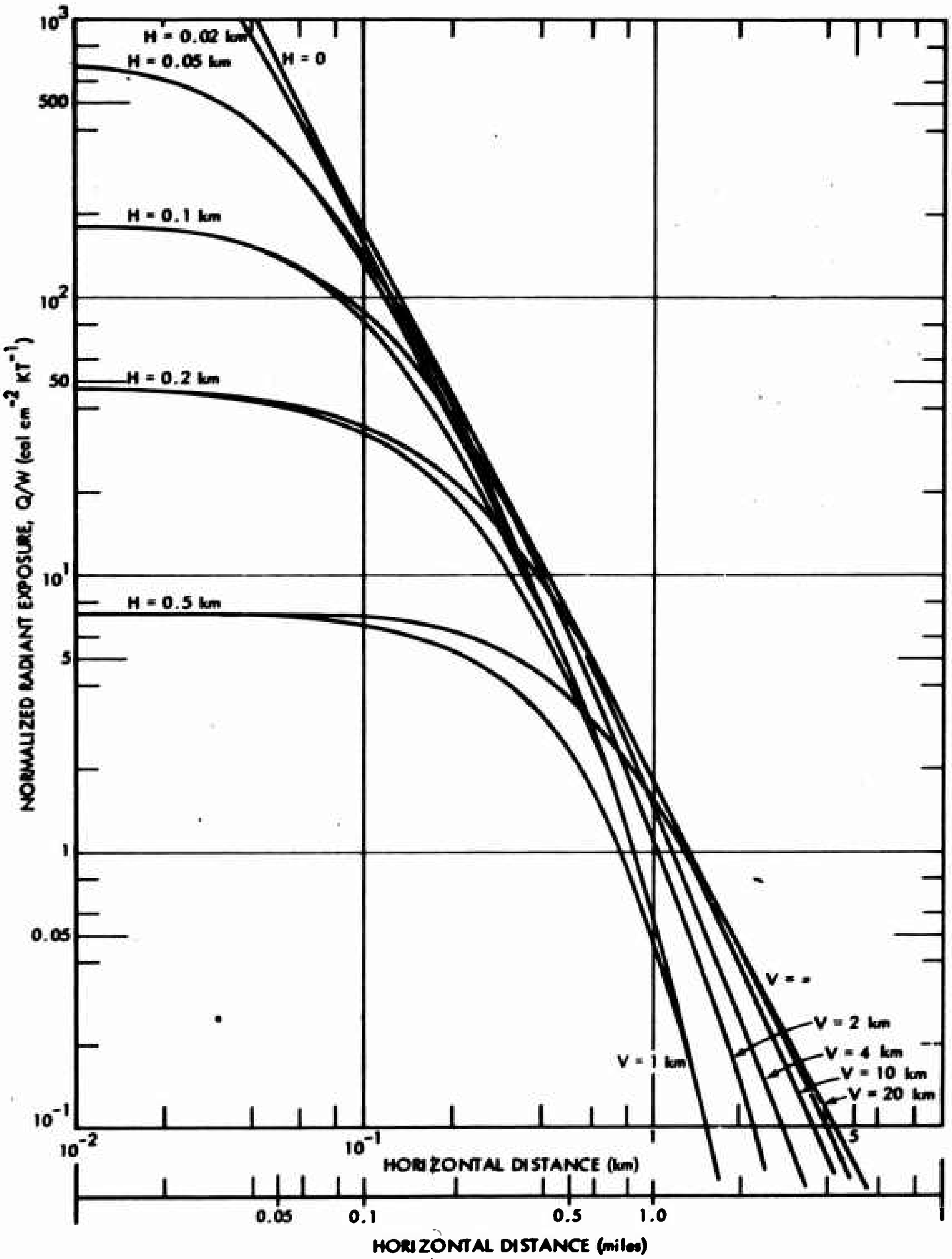

Figure 3-4. Free-field radiant exposures for low air bursts.

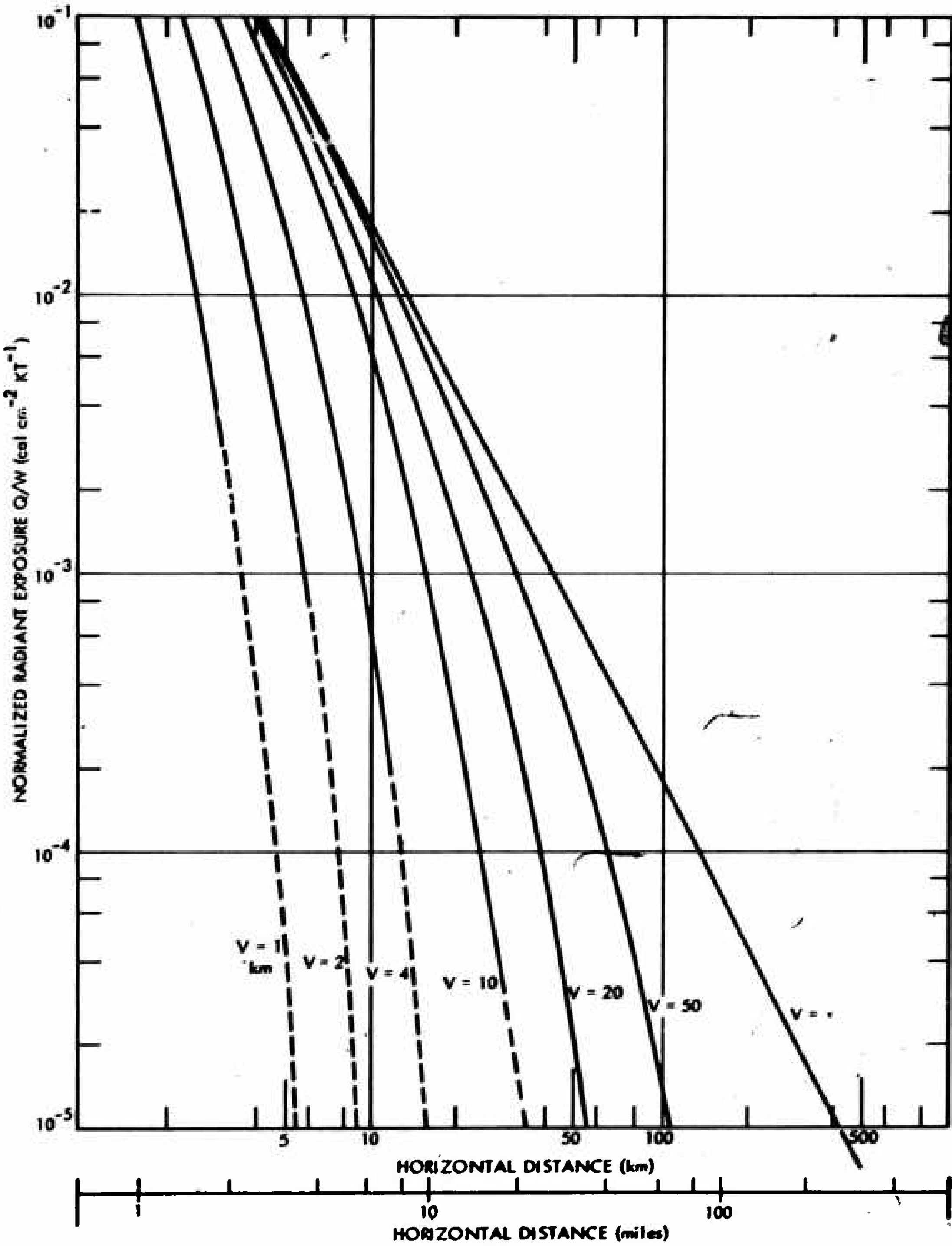

Figure 3-5. Free-field radiant exposures for low air bursts.

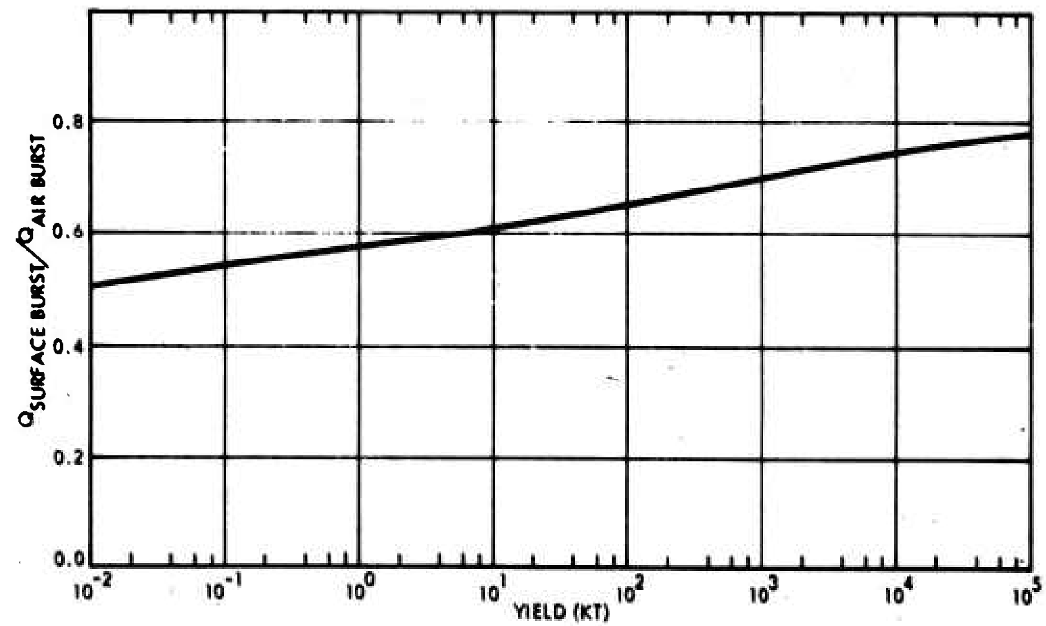

Figure 3-6. Dependence of ratios of radiant exposures from surface and air bursts on yield.

the wildland target. The crowns of the trees, if in a position between a given object and the fireball, will act as a shield and provide protection from thermal radiation. The foliage making up the tree crowns stands a good chance of being exposed to the full free-field radiation loads from air bursts and may be severely dessicated, thermally (even explosively) decomposed, and, at high enough flux levels, flash ignited. Nevertheless, it is not likely to contribute to subsequent sustained fires unless there is appreciable dead material in the canopy. It may, however, materially reduce the exposure of the forest floor by releasing copious quantities of smoke and steam as well as by direct shading.

Neglecting these thermally induced self-protective screening effects,* a crude approximation to attenuation by trees and associated vegetation may be postulated to be proportionate to the extent of the coverage of the field of view of the fireball of tactical yield explosions by the elements of the forest canopy. This is to say that the possibilities of thermal radiation reaching a target on the ground surface depends on the presence and nature of the shadow-producing objects in the vicinity of the target and on the direction of the incident radiation. Height of burst and yield are important geometrical parameters that must be considered. This assumes the sources of thermal radiation to be above the tree tops.**

The foliage of any forest tree in leaf is sufficiently opaque to drastically attenuate thermal radiation reaching the ground beneath, behind, or in the shadow of the tree crown. For nominal explosions it may be assumed that such attenuation will reduce irradiance considerably below critical values.

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* Weapons test data indicate that these effects can be significant. (See Chapter 6.)

** It will be seen in a subsequent discussion that thermal transmission is negligibly small for the low line-of-sight angles corresponding to burst heights less the tree heights, except perhaps for the short transmission paths that accompany bursts in the extreme low-end of the range of yields. For detonations at or below the canopy level having yields measured in tens of tons, significant radiant exposures are possible depending principally on obscuration by tree trunks and undergrowth in the fireball line-of-sight, factors which are determined by the forest characteristics (e.g., tree den ity, tree size and, especially, whether it is a managed or unmanaged forest), but which are not currently amenable to evaluation. However, it can be said with some confidence that significant thermal exposures will not occur, even in a sparsely vegetated forest environment at distances corresponding to peak overpressures of 10 psi or less, because even the full free-field thermal exposure at these distances is only about 4 cal cm^{-2} or less.

Openings in the forest canopy are subject to the same rules of attenuation as the smaller openings in a tree crown through which a portion of the fireball may be visible. Only those portions of surfaces beneath the canopy with fields of view that include the entire fireball will receive unattenuated thermal radiation. Size of openings and tree height are thus other important determinants of the susceptibility of a forest to ignition from an air burst. This indicates the need for on-the-ground or from-the-air appraisal of different forest and presumed explosion situations. This can be done with reasonable accuracy from aerial observation or photographs and much more rapidly than from surface measurements.

Ground checks using all-sky cameras indicate that the probability of seeing any appreciable portion of an extended source (such as nuclear fireball at distances of interest) having an elevation angle less than 15 degrees above the horizon is negligibly small, even in low density stands, and can be neglected except at the edge of a forest stand. In a large proportion of cases of tactical interest, the height of burst is within a fireball radius or two of the ground surface, and for these cases damaging thermal exposures are precluded on the forest floor well within the forest stand at distances where survivable overpressure levels would be experienced. For greater angles of elevation the probability of exposure of a point to a fireball at that elevation angle increases slowly with elevation, approaching, at the zenith, a value that may equal the canopy density as measured by aerial photographs. Such a function for a point source for the so-called "standard Northern European forest"* defined in Table 3-2, is illustrated in Figure 3-7 by the curve labelled Pe (θ), i.e., the probability of exposure of a point on the forest floor by (or equivalently, the percent of forest floor exposed to) a point source of thermal radiation as a function of the line-of-sight elevation angle (in degrees). Over a substantial range of elevation angles, i.e., $15 \le \theta \le 75$; this function can be approximated by Pe (θ) = $0.87\,\theta - 8$.

* The "standard Northern European forest" represents a composite of the characteristics of forests of northern Europe obtained by averaging the features of ten different stands chosen as representative of type (pine woods, spruce and deciduous forests, and mixtures of these) and tree density (range of about 200 to 1000 trees per acre).

Table 3-2. Standard Northern European forest data.

Sites were chosen on flat terrain in Northern Europe having uniform density distributions and generally uniform tree height (not more than 15 percent variation for not less than 90 percent of the trees in the stand). This uniformity is typical of the managed forests of Europe along with a general absence of undergrowth. These characteristics are not common to unmanaged (natural) forests. There is no reason to expect that information derived from these studies are in any way applicable to tropical hardwood forests.

Average maximum crown diameter	3.5 meters
Average effective crown diameter	2.5 meters
Average tree height	15.0 meters
Tree density	0.06 $meter^{-2}$ 243 trees/acre
Tree species	dominantly coniferous

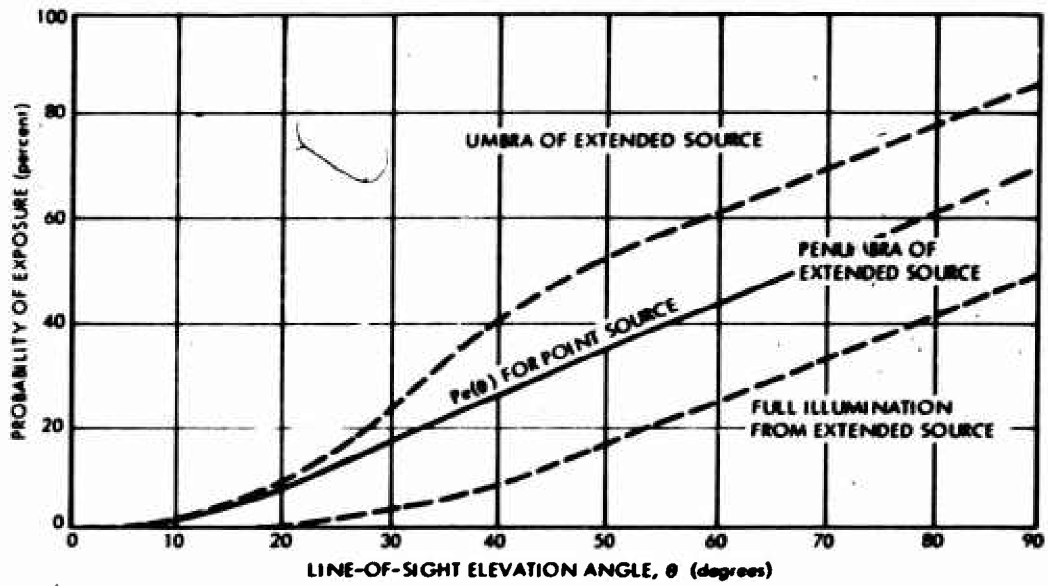

Figure 3-7. Probability of exposure of the forest floor ("standard Northern European forest") as a function of elevation angle; examples of a point source and a spherical source subtending an angle of 10 degrees.

For present purposes, it would be convenient if relationships such as the foregoing probability of exposure function could be interpreted as the fraction of free-field radiant exposure incident on the forest floor. Such an interpretation would be legitimate if the angles subtended by the "holes" in the canopy were generally large compared to the angles subtended by the fireball. This is rarely so, however.

The apparent size of the fireball is obviously a function of both the size of the detonation and the nearness of the point in question. It is noteworthy that for many free-field effects of a detonation, e.g., given levels of overpressure and the thresholds of such thermal effects as ignition of fine fuels and flash burns to exposed personnel, the angle subtended by the fireball at distances of interest are quite insensitive to weapon yield; it is often convenient to treat the apparent fireball size as though it were constant. It is clear, however, that the angle subtended by the fireball is different for different operationally important responses of the target and its occupants. Methods are available for estimating the apparent size of the fireball corresponding to different kinds and levels of damage when such information is useful. Actual fireball radii were given for a wide range of yields at various heights of burst in Chapter 2. Overpressure height-of-burst curves are given in The Effects of Nuclear Weapons (Reference 2). Methods for estimating ignition and flashburn ranges will be presented in subsequent chapters.

Obviously Pe (θ) functions, as illustrated by the "standard Northern European forest" in Figure 3-7, must depend on forest characteristics, notably tree density, with increased dispersion expected toward the larger angles of elevation. The data presently available do not adequately reflect the degree of dispersion nor its dependence on forest characteristics. Some notion of dispersion with tree density can be obtained from Figure 3-8 which displays the range of results.

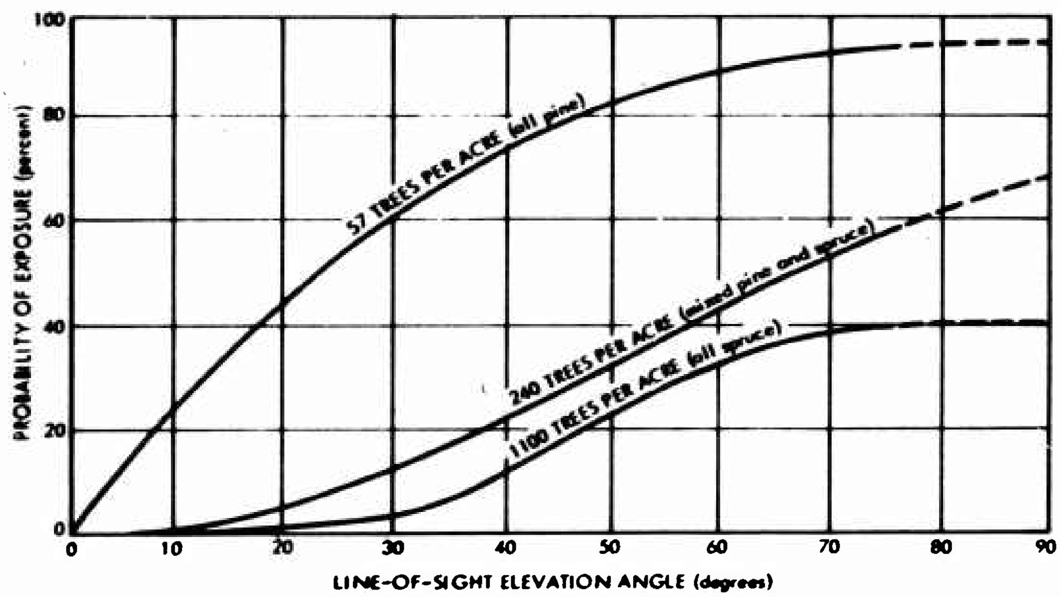

Figure 3-8. Probability of exposure of forest floor for different levels of tree density.

Following intensive aerial inspection of most of the forests of West Germany supported by numerous ground checks, the U.S. Forest Service concluded that tactical yield explosions over managed German forests would produce negligible numbers of fires beneath the tree canopy. Edge effects in these forests, however, are common; fires from these ignitions would spread readily except in the spruce timber type. To indicate the additional shielding by branches and stems, inspection was also made of deciduous forests not in leaf. Thermal energy attenuation was estimated as follows:

Line-of-sight angle (degrees)	Percent of full energy at surface
90	95
60	80
45	60
30	25

Of course these results are high compared to previously shown data for the largely evergreen forests of northern Europe, except for low angles of the line of sight where attenuation is largely independent of the canopy and whether it is in leaf.

The current data base is quite poor, particularly as it applies to unmanaged forests and tropical or temperate broad-leaf forests. Nevertheless, it can be inferred that radiant exposures within forest stands are inadequate to ignite materials beneath the canopy at distances where blast effects are not extreme except, perhaps, in the least densely populated stands (less than 50 to 100 trees per acre). At distances where survival of blast and prompt radiation effects can be expected, radiant exposures would be much less than half the free field over most of the floor of forests having densities of a few hundred or more trees per acre, and probabilities of exposure to the full free-field level would be negligibly small.

3.5 REFERENCES

1. Glasstone, S., ed. The Effects of Nuclear Weapons, United States Atomic Energy Commission, April 1962.

2. Glasstone, S., ed. The Effects of Nuclear Weapons, United States Atomic Energy Commission, Revised Edition, February 1964.

CHAPTER 4

WILDLAND FUEL IGNITION REQUIREMENTS

4.1 INTRODUCTION

Unlike the other damaging effects of nuclear detonations, fire has the capability to grow and spread and thereby destroy a much larger part of the target than was initially affected directly by the detonation. Whether or not fire spreads significantly beyond the area initially ignited, no analysis of incendiary damage can be conducted with confidence regardless of the extent to which the damage may be due to fire spread without a reliable evaluation of the initial incendiary response of the target.

Fires produced directly by a nuclear detonation result from the ignition of lightweight organic material (called tinder by some authors but referred to here as kindling fuels) by the thermal radiation pulse accompanying the detonation. The assessment of incendiary hazard depends upon a number of factors including the thermal radiation distribution over the target, which has been discussed in previous chapters, and on the ignition of the fine kindling fuels present in the forest which will be the subject of this chapter. Wildland fuels are typically a mixture of thin and heavy fuel components. Often the thinner fuels will establish the limiting radiant exposure that will be required to start fires in the mixture. When fuels are dry, ignitions can be expected at quite low levels of radiant exposure, where the incipient fires have a reasonable chance of surviving the subsequent blast effects and of growing into fires that can represent a hazard to military personnel and equipment in the forest. The necessary radiant exposures depend not only on moisture content, but also on the characteristics of the fuel and on disturbing effects of the blast wave that accompanies the thermal radiation pulse that ignites the fuel as well as on weather factors. Ignition thresholds also depend on the orientation of the fuel and on the conditions of the nuclear detonation that determine shape and duration of the thermal-radiation pulse. While it is not currently possible to predict from first principles the ignition thresholds of kindling fuels, it is possible to describe quantitatively their dependence on the factors above and it will be the principal purpose of this chapter to establish these relationships.

4.2 IGNITION THRESHOLDS

Starting with the Trinity shot in 1945 and continuing through to the beginning of the current test ban, various combustible materials have been (intentionally or unintentionally) exposed to the thermal pulse of nuclear detonations, providing some direct evidence of ignition and other damaging effects. Concurrent with these tests and subsequent to them, ignition thresholds have been measured in the laboratory for many of the same and similar substances. Unfortunately, only a few of the weapons-test data are quantitative and are almost entirely confined to ignition by the brief pulses of kiloton-yield airburst in the high-desert environment of the Nevada Test Site. Whereas most of the laboratory data are quantitative, they have often been determined from exposures to pulses that did not have the same pulse shape nor even the same range of irradiances and pulse durations as the full range of nuclear detonations of interest.

In spite of these deficiencies, several important conclusions can be drawn from the data so obtained. For example, it is clear that broadleaf and coniferous litter (mixtures of fine grass, broken leaves and duff, and thin translucent broadleaf leaves) can be ignited by exposures of 2 to 3 calories per square centimeter from low-altitude air burst of yields in the 1- to 20-kiloton range; and heavier leaves (dead grass, conifer needles and fallen nearly opaque broadleaf leaves) can be ignited by exposures of between 3 and 4 calories per square centimeter. The significance of these ignition thresholds is evident when one recognizes that the corresponding peak overpressures are in order of 2 psi and less for free field conditions.

It is also evident from these data that ignition-threshold values increase with the thickness of the kindling fuel, increase with moisture content, are smaller for darker, more opaque materials and increase with the longer-duration pulses of larger-yield weapons. The very limited data available from Pacific tests of large-yield detonations indicate that the ignition thresholds for kindling fuels are on the order of a factor of 2 to 3 larger for megaton-yield detonations. The increase due to moisture contents in equilibrium with air at high relative humidities is ordinarily not more than a factor of 2, perhaps as much as a factor of 3 for some materials. Wet or green leaves, however, are virtually impossible to ignite and even when ignited will not participate in the development of a persistent fire.

There is some evidence that the blast wave may extinguish incipient fires, but the effect has usually been observed in fuels that were constrained from moving with the blast wave and the full impact of this interaction is still not evaluated completely. It is to be noted that at distances close to the detonation where the blast wave arrives early in the thermal pulse, sufficient radiant exposure may follow the passage of the blast wave to reignite fuels and to ignite blast-created debris. This is more likely to occur with larger yields.

Current interpretations of the qualitative effects of blast on the persistence of incipient fires are based largely on experiments where kindling fuels were anchored in place. Had these fuels been free to move with the blast it must be concluded that many of them, even at high overpressures, would have continued to burn and would have been translated for considerable distances as effective fire brands. Fire spread following ignitions by these brands would be significantly influenced by the return flow through the negative blast phase.

4.3 DEPENDENCE OF IGNITION THRESHOLDS ON FUEL PROPERTIES, ENVIRONMENTAL FACTORS, AND BURST CONDITIONS.

4.3.1 Need for a Method of Correlation

The experimental determination of the ignition radiant exposures of all kindling fuels for the necessary variety of conditions and ranges of weapon yields would be a formidable task. At an early stage in the history of investigation of ignition thresholds, it was recognized that it might be possible to use a model kindling fuel and through the use of similitude theory a generally useful technology of the ignition of kindling fuels might be generated - one which could successfully predict the response of untested materials to untried situations. To a large extent this expectation has proven to be so. The success of this correlation method led to an extensive program of experimental study of ignition thresholds in a model kindling fuel (Reference 1). This program resulted in the prediction techniques that are being used today.

4.3.2 Choice of Alpha Cellulose as a Model Kindling Fuel

The bulk of the kindling fuels to be found in the large majority of potential target areas is cellulosic in nature. Although there is increased use of synthetics in urban areas, the kindlings to be found in forest and wildland areas are almost exclusively cellulosic. Accordingly, the appropriate material to use as a model kindling fuel is cellulose. Although the properties of cellulose cannot be varied over a wide range of values, alpha-cellulose papers, prepared by the Forest Products Laboratory, Madison, Wisconsin, provided a very satisfactory idealized kindling fuel for experimental purposes. These papers were produced from a single batch of pure alpha wood pulp. They were made with varying amounts of carbon black added to provide gradations in optical properties from white to black and in a range of thicknesses from .002 inches to .03 inches. They were provided in two densities, nominally 1/2 and 3/4 grams per cubic centimeter which caused them to possess two sets of heat conduction properties.

This cellulosic kindling fuel became the subject of an extended research program. Its ignition behavior under exposure to constant flux levels for varying exposure durations was scrutinized in detail before attempting to establish a predictive methodology from ignition data acquired with simulated weapon pulses. As expected, the data correlation for weapon pulse exposures was of similar form to the correlation for constant-flux (square-wave) exposures and the acquisition and interpretation of data was greatly facilitated by the thorough preliminary study using square-wave exposures.

A significant finding of this early work was the existence of several distinct kinds of ignition and of their relationship to one another in terms of irradiance level and duration of exposure. Transient flaming ignition, a familiar phenomenon in thick fuels, was observed for even very thin kindling fuels exposed to high irradiances for very short times. It was found to be separated from persistent flaming ignition by a clearly defined threshold when exposures were extended to longer durations. Glowing ignition, which is always persistent, was recognized as a separate phenomenon that occurred prior to, or entirely replaced, flaming ignition at low levels of irradiance.

The concept of a critical irradiance, that is, the irradiance level below which ignition would not occur regardless of the length of exposure, was advanced to explain the large increases in ignition thresholds at very low irradiance levels (particularly the lack of correlation for materials of different thicknesses). Based on the data available at that time, the threshold radiant exposure for persistent ignition appeared to increase in proportion to the quarter power of the exposure duration for irradiances significantly greater than critical irradiances. This observation spawned the popular notion, still devoutly held by some, that ignition thresholds scale as the one-eighth power of weapon yield for sea-level bursts. This notion however has not survived the subsequent scrutiny of more extensive data.

4.3.3 Ignition Prediction Method

The method employed here is based on laboratory observations of the response of small model targets of the α-cellulose described above. These targets were geometrically idealized representations of real fuels - typically single flat sheets exposed at normal incidence, except for some limited testing of layered and crumpled arrays. It is not entirely clear to what extent the responses of these idealized targets simulate the responses of such highly complex structures as forests or wheat fields but it is encouraging to note that, to the limited extent such extrapolations have been attempted, they have been remarkably successful.

With some reservations due to the uncertainties mentioned above, it appears that ignition behavior determined for model targets made of alpha cellulose represents fairly well the ignition characteristics of a wide variety of common kindling fuels and can be used as a measure of the incendiary reach of nuclear attack. The responses of such model targets to square-wave thermal pulses have been thoroughly investigated experimentally and are fairly well understood theoretically. The theoretical analysis has proceeded as far as identifying the dimensionless parametric groups in terms of which a universal description of ignition behavior can be provided. A large quantity of experimental data can be correlated using these variables so that this aspect of the method appears to be both reliable and of great generality.

Thermal pulses of nuclear detonations do not possess a rectangular shape. Detonations at low altitude are characterized by the pulse given in "The Effects of Nuclear Weapons" (Reference 2), whereas at intermediate altitudes the pulse may be quite different in shape. A large body of experimental work has verified that the response of materials to ENW pulses can be correlated by the same techniques which apply to rectangular pulses. However, information pertaining to the response of materials to an intermediate pulse shape is sparse and inconclusive. The method employed here as it applies to the intermediate altitude regime is the first approximation. It probably reveals the correct trends, but requires further experimental inputs.

4.3.4 Response to Square-Wave Exposure

Over a wide range of conditions, the ignition by square-wave pulses is governed by heat diffusion through the target material. It may therefore be expected that a general description of the ignition process can be made in terms of a dimensionless quantity such as the Fourier modulus. The square root of the Fourier modulus designated τ is equal to

$$\frac{\sqrt{\alpha t}}{L}$$

where

α = the thermal diffusivity of the material

L = the thickness of the material

t = the time of exposure

and an energy modulus represented by the parameter group* $aQ/\rho cL$

where

a = absorptivity of material

ρc = the volumetric heat capacity

Q = ignition threshold radiant exposure

The validity of this expectation has been verified experimentally. Over a wide range of values of the Fourier modulus, $(0.01 < \tau^2 < 2.0)$ the ignition exposure can be computed by means of a single relationship between the energy modulus and some empirical function of τ which is tabulated in Table 4-1.

For very low values of Fourier modulus, i.e., typically for exposures at very high irradiance levels, ablation of the material from the target surface rather than diffusion of heat governs the ignition process. It has been anticipated by some workers (Reference 3) that for very short, high irradiance exposures, the threshold radiant exposure required to ignite materials would rise sharply. However, the available experimental evidence, which is limited, does not support this contention, but indicates that the ignition requirements level off for $\tau^2 < 0.01$.

At the other extreme (that is, very long exposures or very thin materials) heat losses, principally by convection, appear to dominate. Ignition will therefore occur only if the rate of radiant energy delivery (the irradiance) exceeds, even infinitesimally, the rate of heat loss at the

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* This parameter group is the mean temperature rise of the radiation receiver, if losses are neglected, and therefore, has the dimensions of temperature. The values quoted in this chapter are in degrees Celsius.

Table 4-1. Coordinates of ignition curve (square-wave exposure).

Fourier Modulus (τ^2)	τ	$\alpha Q/\rho c L$ (°C)
0.01	0.100	2170
02	.1415	1860
.04	.200	1550
.06	.245	1420
.10	316	1250
.16	.400	1120
18	424	1090
.20	447	1050
.22	469	1010
24	.490	990
26	.510	950
28	529	930
.30	.548	890
32	566	870
34	.583	840
36	.600	810
38	616	780
.40	.632	760
.44	664	73[illegible]
.48	.692	714
.52	721	700
56	748	690
60	774	680
64	800	683
.70	837	700
74	.860	706
78	884	714
.82	.906	730
.86	928	737
90	.949	745
.96	.98	768
1.02	1.0[illegible]	776
1.10	1.05	810
1.20	1.10	850
1.30	1.14	880
1.40	1.18	910
1.50	1.22	930
1.60	1.26	950
1.70	1.30	960
1.80	1.34	970
1.90	1.38	978
2.00	1.42	982

ignition temperature. This Q versus t time curve approaches a constant asymptotic slope because there is a minimum ignition temperature for long exposure times. It is thus clear that for large values of the Fourier modulus, the ignition requirements can no longer be stated in terms of the Fourier and energy moduli alone For $\tau^2 > 2$, these requirements are given by the expression:

$$\frac{aQ}{\rho c L} = 885\ \tau^{0.3} + 0.4\left(1 - \frac{4}{\tau^4}\right)\frac{t}{\rho c L}\ ; \qquad (4\text{-}1)$$

so that the limiting irradiance, H = Q/t, approaches about 0.4 cal cm^{-2} sec^{-1} asymptotically as τ increases to very large values. Actually, the asymptotic value, called the critical irradiance, is not a fixed value for all fuels, but depends on the opacity and geometry of the material. The nature of this dependence is only partially understood at the present and so the asymptote can be predicted only approximately. It is readily measured in the laboratory, however.

4.3.5 Response to Nuclear Weapon Pulses

It has been found that the response of materials to nuclear-weapon pulses of the type illustrated in Reference 2 can also be described in terms of the Fourier and energy moduli. However, since these pulses do not possess a finite duration, the time to second thermal maximum, t_{max}, is used in the definition of the Fourier modulus. Ignition requirements for this type of pulse as found in the laboratory are given in Table 4-2.

For extremely long pulses, that is $\tau > .52$, ignition thresholds are described by the empirical expression

$$\frac{aQ}{\rho c L} = 1522\ \tau^{0.4} + \frac{2.6\ H_c\ t_{max}}{\rho c L} \qquad (4\text{-}2)$$

where H_c is the critical irradiance.

In the absence of pertinent data, the case of high-altitude pulses may be treated using the rectangular-pulse model (Table 4-1) and an equivalent rectangular-pulse duration. This duration may be defined by

$$t = \beta_t\ t_{80} \qquad (4\text{-}3)$$

Table 4-2. Coordinates of ignition curve (ENW pulse).

Fourier Modulus (τ^2)	τ	$aQ_o/\rho cL$ (°C)
0.0001	0.0100	740
.001	.0316	710
.010	.1000	680
.02	.1415	670
.025	.158	660
.030	.173	650
.035	.187	640
.040	.200	630
.046	.215	600
.050	.224	580
.054	.232	570
.057	.239	560
.060	.245	570
.064	.253	580
.070	.265	600
.076	.276	620
.100	.316	712
.200	.447	1006
.270	.52	1170

where t_{80} is the time required to release 80 percent of the thermal energy* and β_t is an empirical factor which depends on t_{80} and on the material thickness as shown in Table 4-3. The estimates of factor β_t were arrived at

Table 4-3. The factor β_t.

Range of t_{80} (sec)	Thin Materials ($L < .01$ cm)	Thick Materials ($.01 \text{ cm} < L < .1$ cm)
0—1	1	1
1—10	0.6	1
10—100	.3	0.6
100—1000	.3	.3

on the basis of the following considerations:

1. For short duration pulses, i.e., $t_{80} < 1$ second for thin materials and $t_{80} < 10$ seconds for thicker materials, the duration of the equivalent square-wave exposure is comparable roughly to the duration of the pulse because losses are negligible compared to the irradiance level during most of the pulse. Regardless of the shape of the pulse if it delivers a radiant exposure large enough to cause significant effects in a period of less than a second, most of that energy flux must be delivered at irradiance levels which are very large compared to heat losses.

2. For very long exposures, the equivalent square wave is the one having an irradiance level approaching the peak irradiance of the pulse. Accordingly, the equivalent square wave duration becomes a progressively smaller fraction of the pulse approaching some small fraction of it as pulse duration becomes progressively longer. Without more detailed knowledge of the power-time characteristics

* Estimates of t_{80} for some situations can be gotten from classified sources such as the pertinent weapons test reports. In very rough terms its magnitude is on the order of t_{max} for a low-altitude detonation of the same yield. However, in detailed analyses, it may produce a closer fit to observed data than use of t_{max}, and is considered nonmeaningful in certain cases.

of the intermediate altitude burst it is not possible to specify the exact value of the duration of the equivalent square wave expressed as a fraction of t_{80}. But from a cursory examination of pulses for which details are known, especially those of the low-altitude burst, $\beta_t = .3$ appears to be a reasonable approximation.

4.4 COMPARISONS OF PREDICTED AND OBSERVED IGNITION THRESHOLDS

4.4.1 Laboratory Data

Following the completion of work on the correlation of the idealized α-cellulose kindling fuel, attempts were made in the laboratory to validate its ability to predict the ignition thresholds of real kindling fuels (References 4, 5). Since most of the previously available data were for small-yield detonations, the emphasis in this laboratory study was given to simulations of the thermal-radiation pulse of large-yield detonations for which data were lacking. Generally speaking, the results were satisfactory. That is, predictions based on the correlation method were substantiated by experimentally determined values. An important element in the use of the correlation methods for such long duration pulses is the accurate determination of critical irradiances for materials and the dependence of the critical irradiance on the properties of the materials. For this reason a sizeable portion of the effort was given to the determination of critical irradiances and their dependence on the properties of kindling fuels.

The results of this study can be summarized as follows:

1. It was demonstrated that ignition thresholds for cellulosic materials can be estimated satisfactorily by computational techniques based on the correlation method. Thinner, less-opaque cellulosic materials exhibited threshold values that increased somewhat less steeply with increasing pulse duration than calculations predict, suggesting that changes in optical properties of these fuels during exposure significantly affect their behavior.

2. Ignition thresholds of materials were found to be independent of the size of the exposed area, except for areas of exposure smaller than about 1 square inch. The most conclusive evidence of this came from comparisons of independently determined values of the critical irradiance for materials exposed to large-and small-area sources.

3. Critical irradiance values, which are extremely useful for estimating ignition thresholds for very long pulses, were reported for a variety of materials. While critical irradiance values can be readily obtained experimentally for most materials of interest, the results of this study showed that when the critical irradiances are not available, they can be reliably estimated even for geometrically complex fuels, without resorting to direct measurement. An empirical function relating critical irradiance to optical thickness was presented for making such estimates.

4. Finally, on the basis of the results it was concluded that current ignition data and the available computational techniques are of adequate reliability for weapons effects purposes, particularly in relation to the uncertain state of related aspects of the thermal radiation problem, notably the atmospheric transmission problem.

4.4.2 Weapon Test Data

Ignition data acquired at weapons tests are compared here with values predicted by the correlation technique developed empirically in the laboratory using alpha cellulose as a model kindling fuel. The validity of the correlation method can be demonstrated most convincingly if it successfully predicts the responses of a variety of real kindling fuels exposed to the thermal pulse of actual nuclear detonations. Unfortunately, for many reasons, including (1) the lack of environmental control and knowledge of the environment, (2) insufficient back-up measurement of radiant exposure, and (3) the widely spaced locations of specimen stations, the field data either are unreliable or at best they broadly bracket the ignition thresholds. Moreover, the property values of the test specimens that are needed if predictions are to be made by the correlation method are not always reported and must be surmised from descriptive information. Nevertheless, a resonably good job of predicting the test results can be accomplished as shown in Table 4-4. The agreement is encouraging, but lacks the convincing impact that it might have were more complete and reliable test data available.

Table 4-4. Comparison of weapon-test data with predictions based on correlation model.

WEAPON TEST	Yield (KT)	t_{max} (sec)	Horsehair Lichen: Test Data*	Horsehair Lichen: Calc. Values	Cheatgrass: Test Data*	Cheatgrass: Calc. Values**	Desert Needlegrass: Test Data*	Desert Needlegrass: Calc. Values**	Wheatstraw: Test Data*	Wheatstraw: Calc Values	Beech Leaves, Weathered: Test Data*	Beech Leaves, Weathered: Calc Values	Madrone, Weathered: Test Data*	Madrone, Weathered: Calc Values	Coulter Pine Needles: Test Data*	Coulter Pine Needles: Calc Values	Ponderosa Pine Needles: Test Data*	Ponderosa Pine Needles: Calc Values	**
			IGNITION THRESHOLDS (cal cm^{-2})																
BUSTER																			
Easy	31	0.190					3.7 (4)	7.5	4.6 (6)	9.5							11.1 (7)	10.4	9.6
SNAPPER																			
3	31	.185	5 (7.9)	5.1	4.3 (7.1)	5.2	3.0 (·)	8.3	<8.9 (6.3)	9.6	3.4† (9.5)	5.2	6.1-7.3 (9.0)	8.3	7.3-8.9 (7.4)	9.6	7.3-8.9 (7.4)	10.4	9.7
4	19	.155	5.3 (14)	5.7	6.6 (10.6)	5.4			8.2 (10.1)	9.8	5.3 (13.6)	5.4	5.3-6.6 (11.9)	8.6	<10.8 (11.4)	9.6	8.2-10.8 (12.6)	10.8	9.9
UPSHOT/KNOTHOLE																			
4	11	.103															<4.8 (5.4)	9.4	6.8
9	26	.179															6.3-7.7 (4.4)	9.5	8.8
10	15	.138															<9.5 (5.8)	9.2	8.0

Two Columns of Calc. Values: 1st based on average thickness of needles; 2nd on thinnest needles.

* Estimated moisture contents (expressed as percent of dry weight) are given in parentheses
** Calculated values are based on finest particles
† Possibly a spurious value. Other samples located to receive exposures up to 7.3 cal cm^{-2} didn't ignite
(·) Unknown but assumed to be 8% for purposes of calculation

4.5 ESTIMATING IGNITION THRESHOLDS FOR WILDLAND FUELS

4.5.1 Detailed Methods of Evaluation

It is implicit in the foregoing discussion of comparisons between data and predictions that methods exist for evaluating ignition-threshold radiant exposures of a variety of kindling fuels for a wide range of conditions, including extensive variations in weapon yields and burst heights. Indeed such methods do exist and with them predictions can be made knowing only a few physical properties of the fuel and the appropriate dependence of t_{max} on yield and burst height.

The job of estimating the necessary physical properties of every material of interest is not as formidable as it might as first seem because the more difficult-to-measure properties such as diffusivity, heat capacity, and moisture content exhibit a regular dependence on such readily determined properties of the materials as thickness and weight per unit area and on the relative humidity of the local environment. Table 4-5 lists a number of wildland kindlings and their pertinent properties. The dependence of moisture content on relative humidity is discussed in Chapter 8. There is no sinple method for determining the moisture content of wildland fuels in place. Section 8.2.2 gives useful procedures for making reasonable estimations.

The generalized ignition-behavior correlation function is available in graphical as well as tabular form. Coordinates of the function for small values of τ are listed in Table 4-2 and for larger values of τ can be calculated from Equation 4-2. Generally, the procedure of evaluation is to calculate ignition threshold values for dry cellulose and then to correct for moisture content by applying the expression

$$Q = Q_0 (1 + fm)$$

where fm is a function of the moisture content in percent of dry weight. The function f is a constant, 0.032, for amorphous cellulose sheets varying in thickness and density over a wide range of moisture contents. For structurally differentiated wildland fuels, however, the function, as measured in the laboratory for a number of fuels over the range of 2 to 20 percent moisture content, was found to be related to fuel thickness and density in the form of $(\rho L)^{\frac{1}{2}}$. This relationship is considered to be valid for moisture contents up to 30 percent, the limit beyond which wildland fuels will not sustain ignition. Values of $(\rho L)^{\frac{1}{2}}$ are listed in Table 4-5. An example of its application to a representative wildland fuel is shown in Figure 4-1. These elements of the procedure for evaluating ignition thresholds can be incorporated into computer programs with suitable relationships for solving numerical problems in terms of the conditions of nuclear detonations.

Table 4-5. Physical and thermal properties of forest fuels.

Grasses and Other Fine Fuels	Thickness (L)	Specific Gravity (ρ)	Thermal Conductivity (k)	Thermal Diffusivity (α)	$\frac{\sqrt{\alpha}}{L}$	$\rho c L$	Absorptivity** (a)	$(\rho L)^{1/2}$
	cm	g/cm^3	$10^{-4}\frac{cal}{cm^2\text{-}sec(°C/cm)}$	$10^{-3}\frac{cm^2}{sec}$	$\frac{1}{sec}$ 0.5	$10^{-3}\frac{cal}{°C/cm^2}$	Dimensionless	$\frac{cal}{°C/cm^2}$
Horsehair lichen (Alectoria jubata)	0.002	0.65	3.70	1.90	21.80	0.39	0.4	9.75×10^{-4}
Cheatgrass-seedpod (Bromus tectorum)	0.003	0.37	2.35	2.12	15.40	0.33	0.3	1.11×10^{-3}
Wiregrass (Aristrida stricta)	0.007	0.67	3.77	1.88	6.20	1.41	0.5	2.8×10^{-3}
Desert stipa (Stipa spp.)	0.007	0.53	3.15	1.98	6.40	1.11	0.4	2.8×10^{-3}
Cheatgrass-leaves (Bromus tectorum)	0.011	0.25	1.76	2.35	4.40	0.82	0.3	2.7×10^{-3}
Harding grass (Phalaris tuberosa var stenoptera)	0.015	0.39	2.45	2.10	3.06	1.76	0.5	3.5×10^{-3}
Sedge (Carex geyeri)	0.017	0.51	3.00	1.96	2.60	2.60	0.5	5.2×10^{-3}
Wheat straw (Triticum spp.)	0.037	0.35	2.25	2.14	1.25	3.89	0.6	6.5×10^{-3}
Cheatgrass stalks (Bromus tectorum)	0.053	0.36	2.29	2.12	0.87	5.73	0.3	1.9×10^{-2}
Hardwood and shrub leaves								
Beech (Fagus spp.)	0.009	0.39	2.45	2.10	5.10	1.05	0.6	1.76×10^{-3}
Chestnut oak (Q. montana)	0.018	0.37	2.35	2.12	2.56	2.00	0.8	2.5×10^{-3}
Scarlet oak (Q. coccinea)	0.018	0.59	3.40	1.92	2.44	3.19	0.8 0.7	4.0×10^{-3} 4.6×10^{-3}
Lauraceae-S.E. Asia (Lauraceae spp.)	0.022	0.46	2.80	2.03	2.05	3.04	0.7	4.3×10^{-3}
Litsea (Litsea spp.)	0.022	0.33	2.14	2.16	2.11	2.18	0.6	3.6×10^{-3}
Rhododendron (Rhododendron catawbiense)	0.025	0.50	2.95	1.97	1.78	3.75	0.8	4.7×10^{-3}
Madrone (Arbutus menziesii)	0.028	0.45	2.75	2.04	1.61	3.79	0.8 0.6	4.7×10^{-3} 6.3×10^{-3}
Arrowleaf balsam root (Balsamorhiza sagittata)	0.028	0.24	1.71	2.37	1.74	2.02	0.7	2.9×10^{-3}
Oregon grape (Berberis repens)	0.031	0.34	2.19	2.15	1.50	3.16	0.6	5.3×10^{-3}
Service berry (Amelanchier spp.)	0.032	0.35	2.24	2.14	1.44	3.36	0.6	5.6×10^{-3}
Messmate stringybark (Eucalyptus obliqua)	0.032	0.58	3.34	1.92	1.37	5.57	0.8	7.0×10^{-3}
Conifer type leaves and needles								
Western larch (Larix occidentalis)	0.022	0.62	3.53	1.90	1.98	4.1	0.7	5.9×10^{-3}
Redwood (Sequoia sempervirens)	0.046	0.42	2.60	2.06	0.99	5.79	0.8	7.2×10^{-3}
Western red cedar (Thuja plicata)	0.050	0.41	2.53	2.06	0.91	6.15	0.8	7.7×10^{-3}
Chamise (Adenostoma fasciculatum)	0.055	0.35	2.24	2.14	0.84	5.78	0.6	9.6×10^{-3}
Douglas-fir (Pseudotsuga menziesii)	0.058	0.56	3.24	1.94	0.76	9.75	0.8	12.2×10^{-3}
Shortleaf pine (Pinus echinata)	0.058	0.52	3.05	1.96	0.76	9.05	0.8	11.3×10^{-3}
Lodgepole pine (Pinus contorta)	0.062	0.56	3.24	1.94	0.71	10.4	0.8	13.0×10^{-3}
Coulter pine (Pinus coulteri)	0.066	0.46	2.80	2.03	0.68	9.12	0.8	11.4×10^{-3}
Ponderosa pine (Pinus ponderosa)	0.069	0.51	3.00	1.96	0.64	10.6	0.8	1.32×10^{-2}
Engelmann spruce (Picea engelmannii)	0.074	0.56	3.24	1.93	0.59	12.4	0.7	1.8×10^{-2}

* For all cellulosic fuels, the heat capacity, c, is taken to be a constant $0.3\frac{cal}{°C, g}$

** When two values are given in this column and the one following it, the lower value of the absorptivity (and hence the larger value of $\rho cL/a$) are for newly fallen leaves. All other values are for weathered materials. Few of these absorptivities have actually been measured. Most are estimated from the appearance of the material.

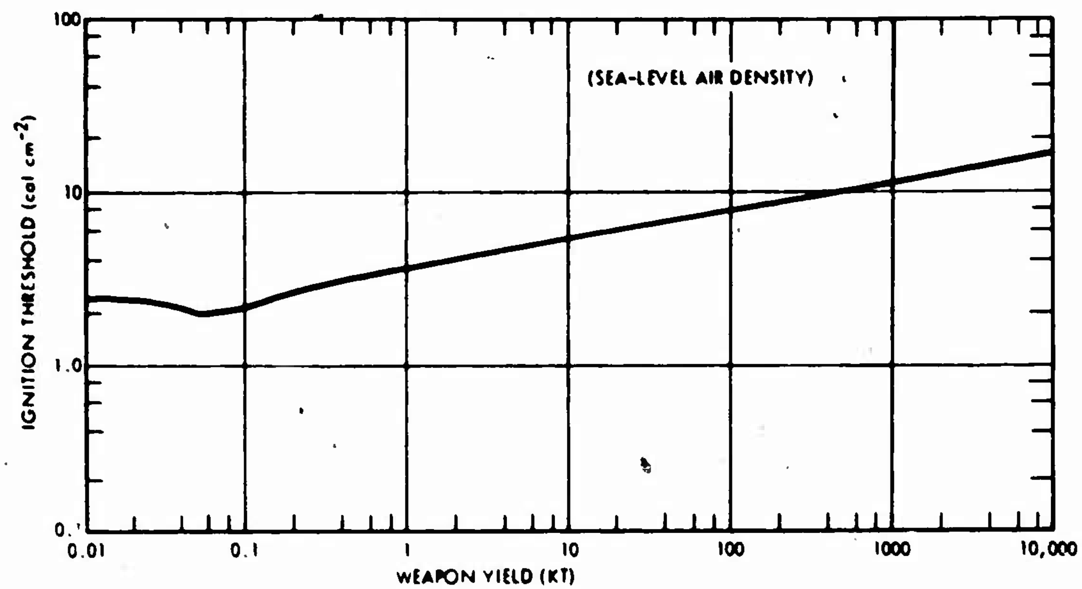

Figure 4-1. Threshold radiant exposures for ignition of a representative Class III forest fuel (grass, bone dry).

4.5.2 Methods of Approximation

As a substitute for the elaborate methods given above, there is a requirement for rough estimation of ignition thresholds when values are not available in either tabular or graphical form. The following equations represent approximations to the ignition correlation patterns derived from idealized alpha-cellulose kindling fuel.

$$\frac{aQ_0}{\rho cL} = 750(1 - \tau) + \frac{t_{max}}{\rho cL} \; ; \; \tau < 0.25 \qquad (4\text{-}4)$$

$$\frac{aQ_0}{\rho cL} = 2250\,\tau + \frac{t_{max}}{\rho cL} ; \; 0.25^{*} \le \tau < 0.52 \qquad (4\text{-}5)$$

$$\frac{aQ_0}{\rho cL} = 1522\,\tau^{0.4} + \frac{t_{max}}{\rho cL} \; ; \; \tau \ge 0.52 \qquad (4\text{-}6)$$

Using these relationships, the ignition thresholds for dry materials can be approximated and these can then be translated into ignition thresholds for moist fuels using the relationship

$$Q = Q_0 \left(1 + (\rho L)^{\frac{1}{2}} h\right) \qquad (4\text{-}7)$$

where h is the local relative humidity in percent.

The use of Equations 4-4, 4-5, and 4-6 for approximating ignition thresholds of kindling fuels can be substantially simplified by noting the values of physical properties of the wildland kindling fuels listed in Table 4-5. From these values it is a straightforward task to calculate the groups of property values that are required by the approximating equations. These also are listed for each of the fuels in the table. It is noteworthy that whereas the thickness of these materials varies over a fairly wide range, and there is a fair degree of variation in density, the thermal diffusivity does not vary substantially, having values from about 1.9 to 2.4 x 10^{-3} cm^2 sec^{-1}. Values of the product ρcL vary principally from variations in thickness alone.

The use of Equation 4-4 is limited to values of τ less than 0.25. Therefore, since a is approximately a constant value of 2 x 10^{-3}, this equation applies to t_{max} values ranging from 10^{-4} seconds for the thinnest materials listed, a value well below our range of consideration, to

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* For $\tau < 0.25$ this expression describes the threshold of transient ignition, i.e., ignition that fails to support itself beyond the end of the exposure.

about 0.2 seconds for some of the thicker pine needles, corresponding to low-altitude detonations of nominal yield (about 20 KT). Accordingly, this equation would not be used for any consideration of ignition of wildland fuels by large-yield detonations. Inasmuch as t_{max} values appearing in Equation 4-4 will always be less than about 0.2 second for the materials listed, we may then neglect the second term and the equation simplifies to

$$Q_0 = 750 \left(\frac{\rho c L}{a}\right) (1 - \tau) \qquad (4\text{-}8)$$

Equation 4-5 applies to values of τ between 0.055 and 0.27. Therefore, its use is limited to t_{max} values less than about 0.5×10^{-3} seconds for the thinnest materials, which is still below the range of our consideration. Its use is also limited to a range of t_{max} values from about 0.1 to 0.7 second for pine needles and other thick materials, which carries it from about the nominal yield range to almost the megaton range. In the case of thickest fuels, neglect of the second term in Equation 4-5 will introduce some error, although its magnitude will be no more than about 10 percent, and considering the approximate nature of the estimating procedure, its neglect is probably justifiable. Accordingly, Equation 4-5 simplifies to

$$Q = 2250 \left(\frac{\rho c L}{a}\right) \tau \qquad (4\text{-}9)$$

Equation 4-6 applies to all values of τ larger than 0.52. For the thinnest materials encountered in the wildlands, Equation 4-6 is the only equation required regardless of the duration of the thermal pulse. For thicker materials its use is limited to larger detonations and longer pulse durations and for the thickest materials to be found in the wildlands that may be considered to be kindling fuels, its use is limited to detonations of megaton-yield weapons. In using Equation 4-6 the second term cannot be neglected. In fact, for very long duration pulses the second term dominates, and ignition thresholds expressed in calories cm^{-2} numerically approximate t_{max} in seconds. This approximation, however, can only be applied with confidence when t_{max} values are so large that peak irradiances for threshold exposures approach the critical irradiance values of materials. For the thinnest materials to be found in the wildlands this requires exceedingly prolonged pulse durations (t_{max} values measured in tens of seconds), and for thicker materials, the requisite pulse durations are yet longer. Therefore, this simplification is of little practical value, and the final form of the equation is

$$Q_0 = 1522 \left(\frac{\rho c L}{a}\right) \tau^{0.4} + \frac{t_{max}}{a} \qquad (4-10)$$

In summary, ignition thresholds can be estimated with some confidence for untested materials and for untried situations using the current correlation method. Both detailed procedures and simplified approximations are available. In view of the many uncertainties involved in the evaluation of the fire response of complex wildland targets to nuclear detonations, the accuracy provided by the simplified approximations is generally adequate.

4.6 REFERENCES

1. Martin, S. Ignition of Organic Materials by Radiation, Fire Research Abstracts & Reviews 6, 85, 1964.

2. Glasstone, S., ed. The Effects of Nuclear Weapons, United States Atomic Energy Commission, Revised Edition, February 1964.

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4. Martin, S. B., and N. J. Alvares. Ignition Thresholds for Large-Yield Nuclear Weapons, USNRDL-TR-1007, April 1966.

5. Bracciaventi, J., et al. Radiant Exposures for Ignition of Tinder by Thermal Radiation from Nuclear Weapons, NASL Project 9400-12, Final Report, July 6, 1966.

CHAPTER 5

NON-THERMAL EFFECTS

5.1 INTRODUCTION

This chapter covers the non-thermal effects on forests of three burst parameters: (1) nuclear radiation, (2) air blast, and (3) ground shock. The synergisms of these three parameters, as well as thermal effects, are also considered.

The first parameter discussed is nuclear radiation. The forest attenuates radiation from a nuclear burst, but the radiation has no immediate effect on the forest. Radioactive fallout, however, produces a delayed reaction, slowly killing exposed coniferous trees, thereby increasing eventual flammability. Presence of such contamination above 0.5 roentgens per hour (R/hr) measured dose rate is also an operational hazard.

The second parameter discussed is air blast. Air blast causes tree blowdown within the forest and the translation of the fallen tree stems and other debris.

The third parameter considered is ground shock. Consideration is given to the effect of the forest on ground motion and the possible effect of ground motion on the trees within a forest.

5.2 NUCLEAR RADIATION

5.2.1 Initial Gamma Radiation

An accurate determination of the effect of forests on the initial gamma radiation received at points near the forest floor requires the expenditure of a far greater effort and the use of much more highly sophisticated procedures than have been possible up to this time. Calculations were made for DISTANT PLAIN (Reference 1)(Canadian coniferous forest) and BLOWDOWN (Reference 2) (Australian rain forest), and the observed attenuations were within a factor of 1.5 of those calculated. Curves showing the average gamma attenuation factors obtained are illustrated in Figure 5-1 for the two burst heights and for the two forest types. Figures 5-2 through 5-7 present curves of the gamma dose versus slant range for yields of 0.13, 1, and 10 KT at heights of 0 and 136 feet for the no-forest situation and for the DISTANT PLAIN and BLOWDOWN cases.

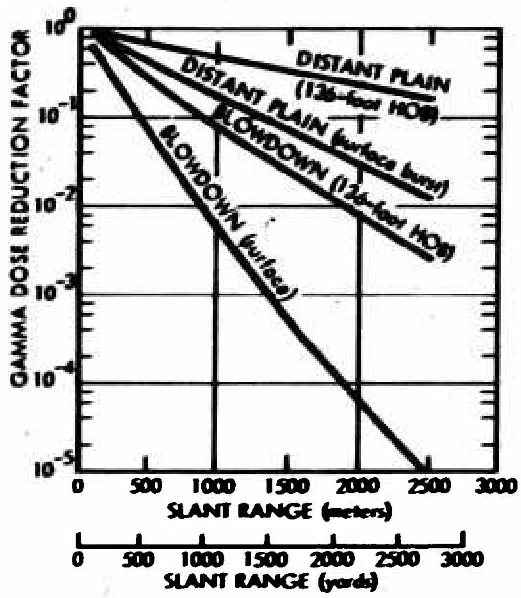

Figure 5-1. Gamma attenuation factors for the Distant Plain and Blowdown forests.

5.2.2 Neutron Radiation

A determination of the protection offered by forests against the neutron radiation from nuclear weapons will require extensive experimental or theoretical programs. Simulation experiments involving the use of neutron sources in scaled-down versions of the forest, or theoretical calculations using transport codes and Monte Carlo techniques will be required if credible results are to be obtained. The following non-rigorous approach was based on the assumption that the attenuation of neutrons by forests can be expressed by $e^{-N\Sigma x}$ where

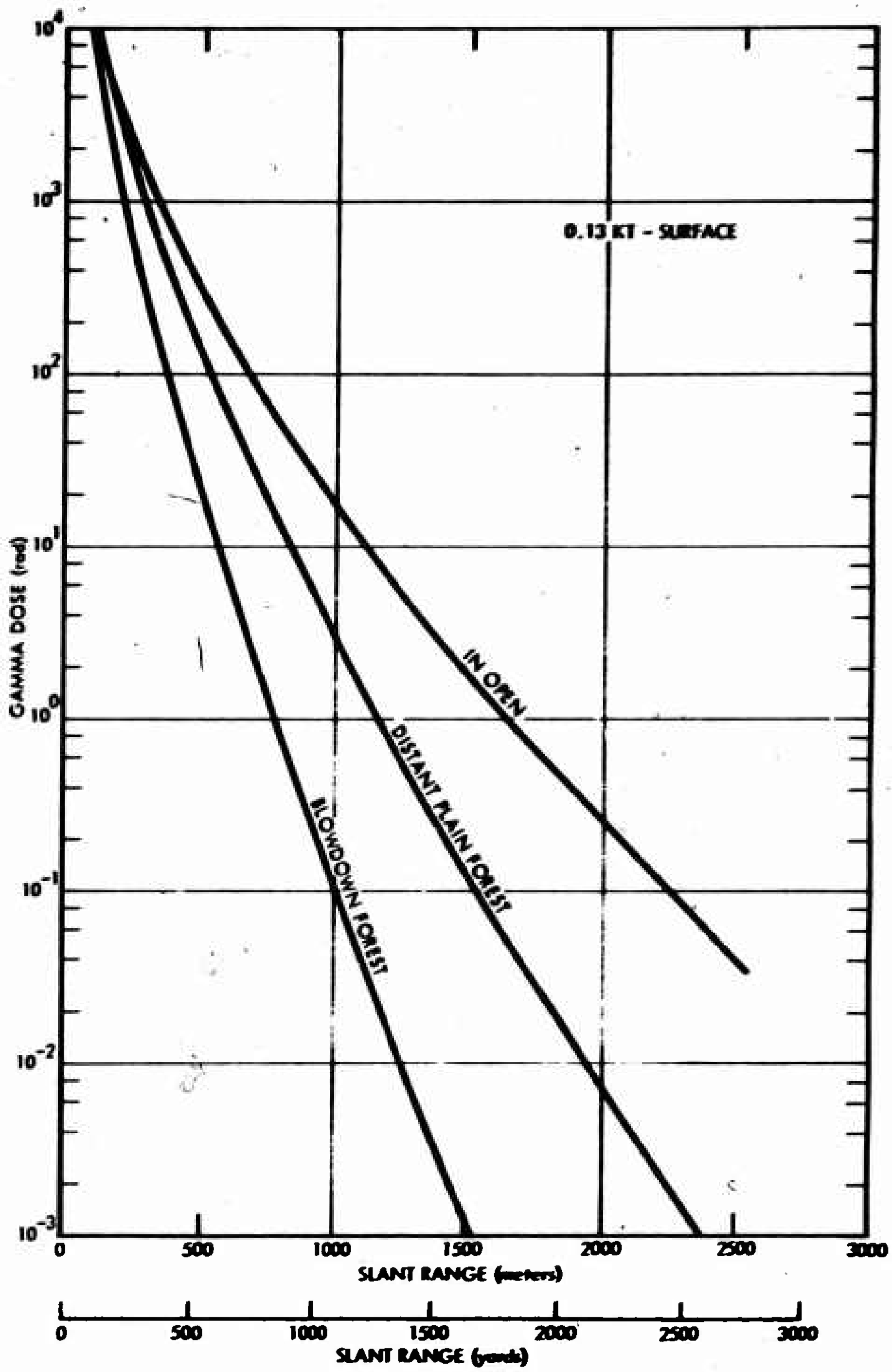

Figure 5-2. Gamma dose as a function of slant range for a 0.13-KT surface burst.

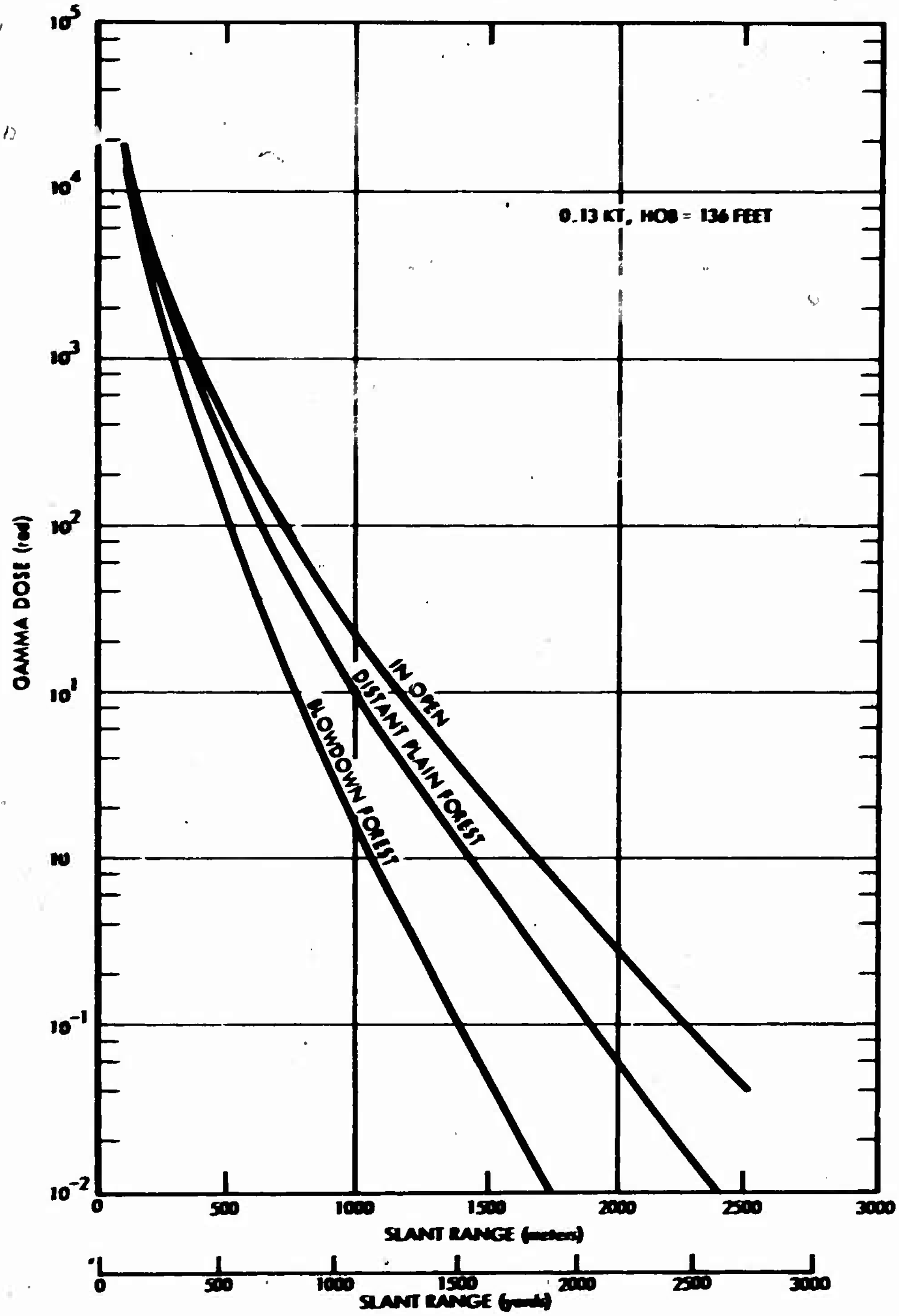

Figure 5-3. Gamma dose as a function of slant range for 0.13-KT at 136 feet height of burst.

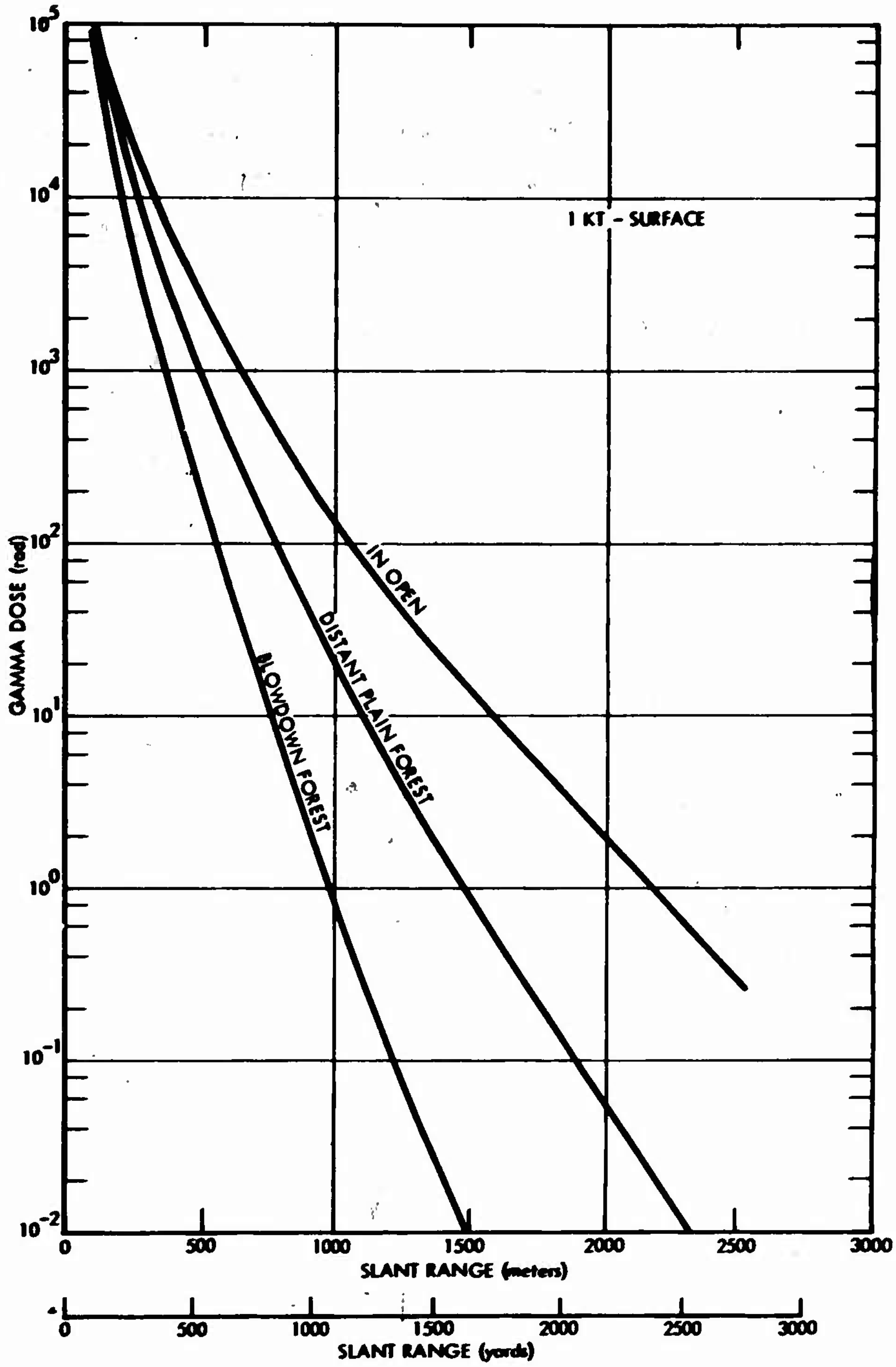

Figure 5-4. Gamma dose as a function of slant range for a 1-KT surface burst.

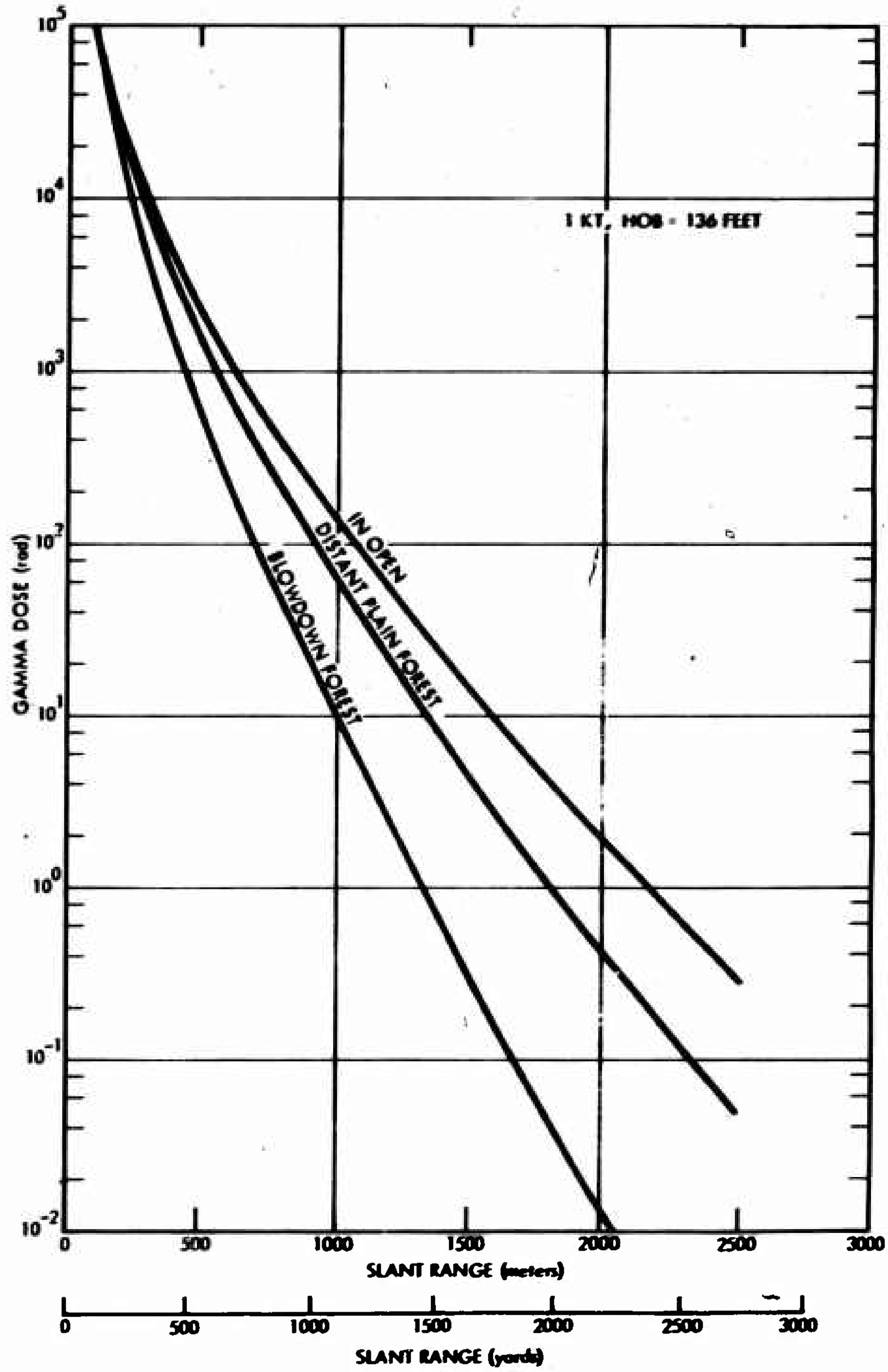

Figure 5-5. Gamma dose as a function of slant range for 1-KT at 136 feet height of burst.

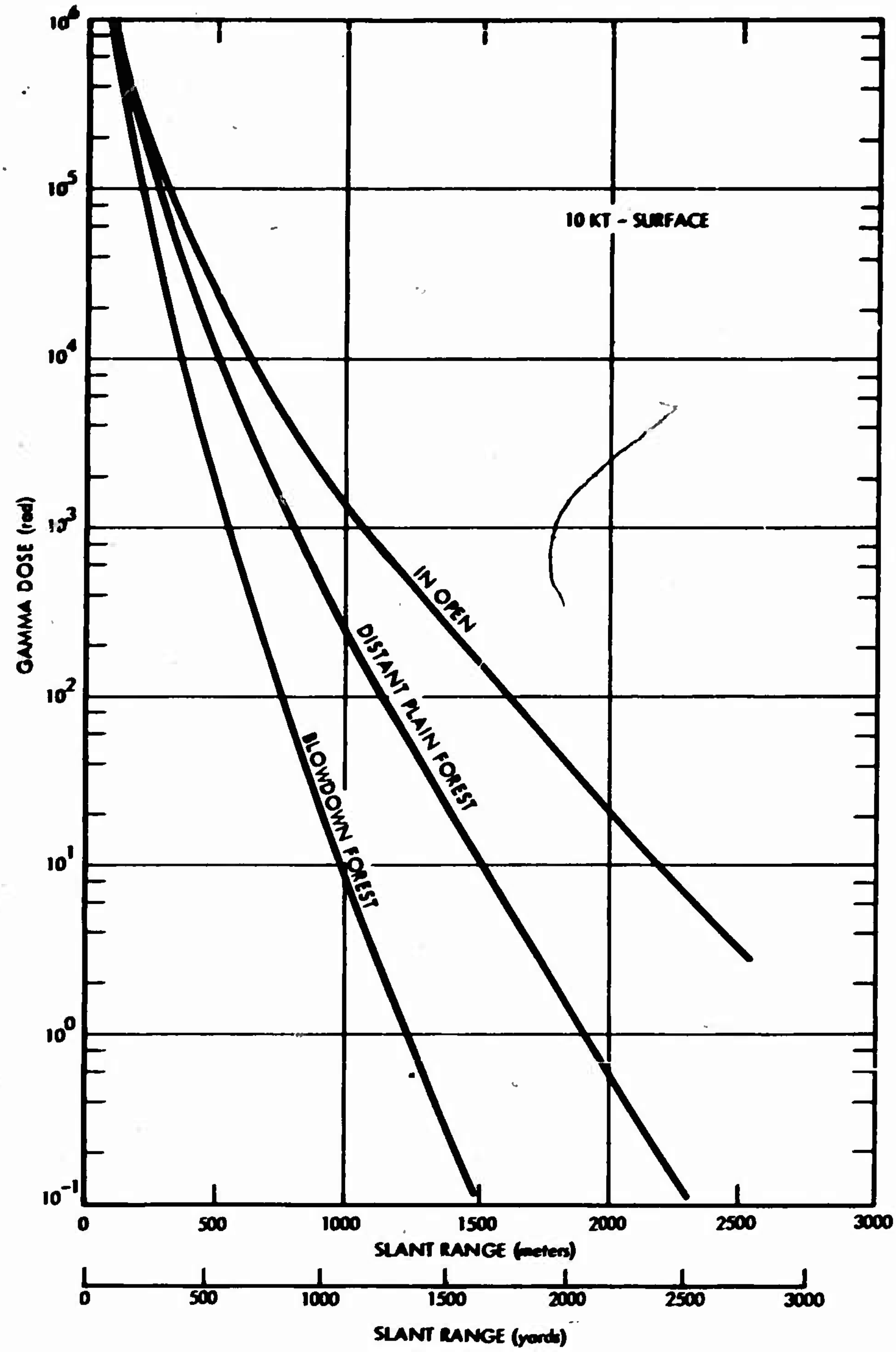

Figure 5-6. Gamma dose as a function of slant range for a 10-KT surface burst.

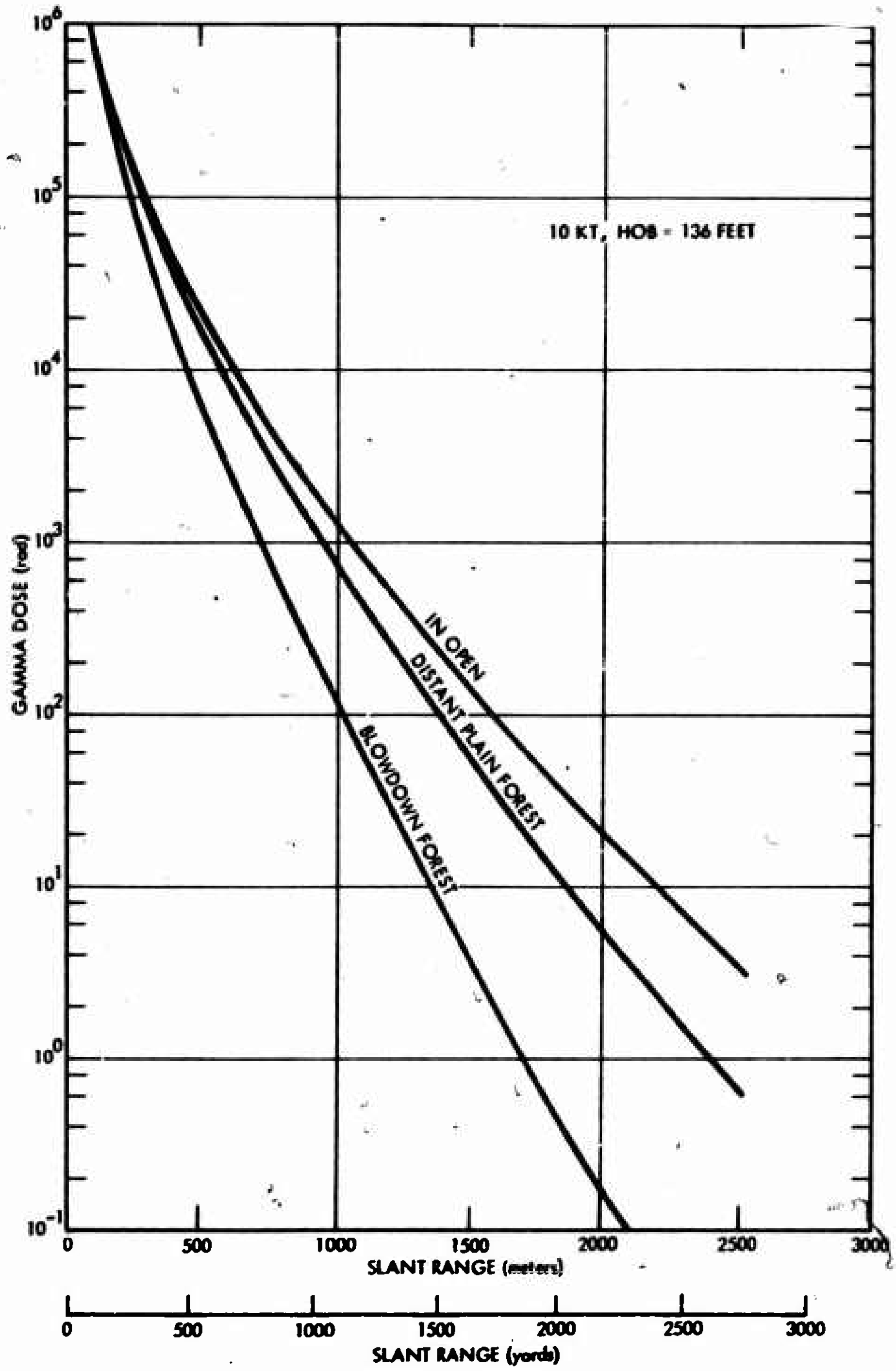

Figure 5-7. Gamma dose as a function of slant range for 10-KT at 136 feet height of burst.

N = average number of atoms per unit volume
Σ = absorption cross section
X = total path through wood.

This approach neglects all factors except wood and takes advantage of the known atomic composition of wood and established attenuation data for the atoms present.

Wood contains approximately one-half the number of hydrogen atoms per cubic centimeter as does water and it also contains about the same number of carbon and oxygen atoms per cubic centimeter as there are oxygen atoms in water. Assuming that the cross sections of oxygen and carbon are similar for a fission neutron spectrum and using Table 6-6 (Fission neutron attenuation by hydrogen in water) and Figure 6-9 (Fission neutron dose in water) in Fundamental Aspects of Reactor Shielding (Reference 3) attenuation factors for various thicknesses of wood were obtained.

The resulting attenuation factors are shown in Figure 5-8 for two burst heights and the two forest types. Figures 5-8 through 5-11 show the neutron dose versus slant range for the no-forest situation and for the BLOWDOWN and DISTANT PLAIN forests.

5.2.3 Residual Radiation

BLAST DAMAGE AREA. Radioactive fallout produced by nuclear weapons detonated on or near the forest floor will be transported by the winds above the canopy to be deposited in the same way as for detonations in any land area. The cleared area outside the crater can be expected to have H + 1 hour gamma exposure rates of several thousand roentgens per hour (R/hr) for all yields. Similarly, for a surface burst the smooth-plane exposure rates in the downwind sector of the tree blowdown area will be a few thousand R/hr at H + 1 hours, while in the region of defoliation due to blast, exposure rates can be expected to range from several hundred R/hr for very low yields to a few thousand R/hr for higher yields. Estimates for these smooth-plane exposure-rate ranges are shown graphically in Figure 5-12. The radii of effects used in constructing the figure were obtained or extrapolated from information contained in Bowe 1964 (Reference 4) and UK 1966 (Reference 5) and are shown in Table 5-1. The actual exposure rates experienced in the blowdown and defoliated regions of the forest would be expected to be somewhat less than indicated in Figure 5-12 because of ground

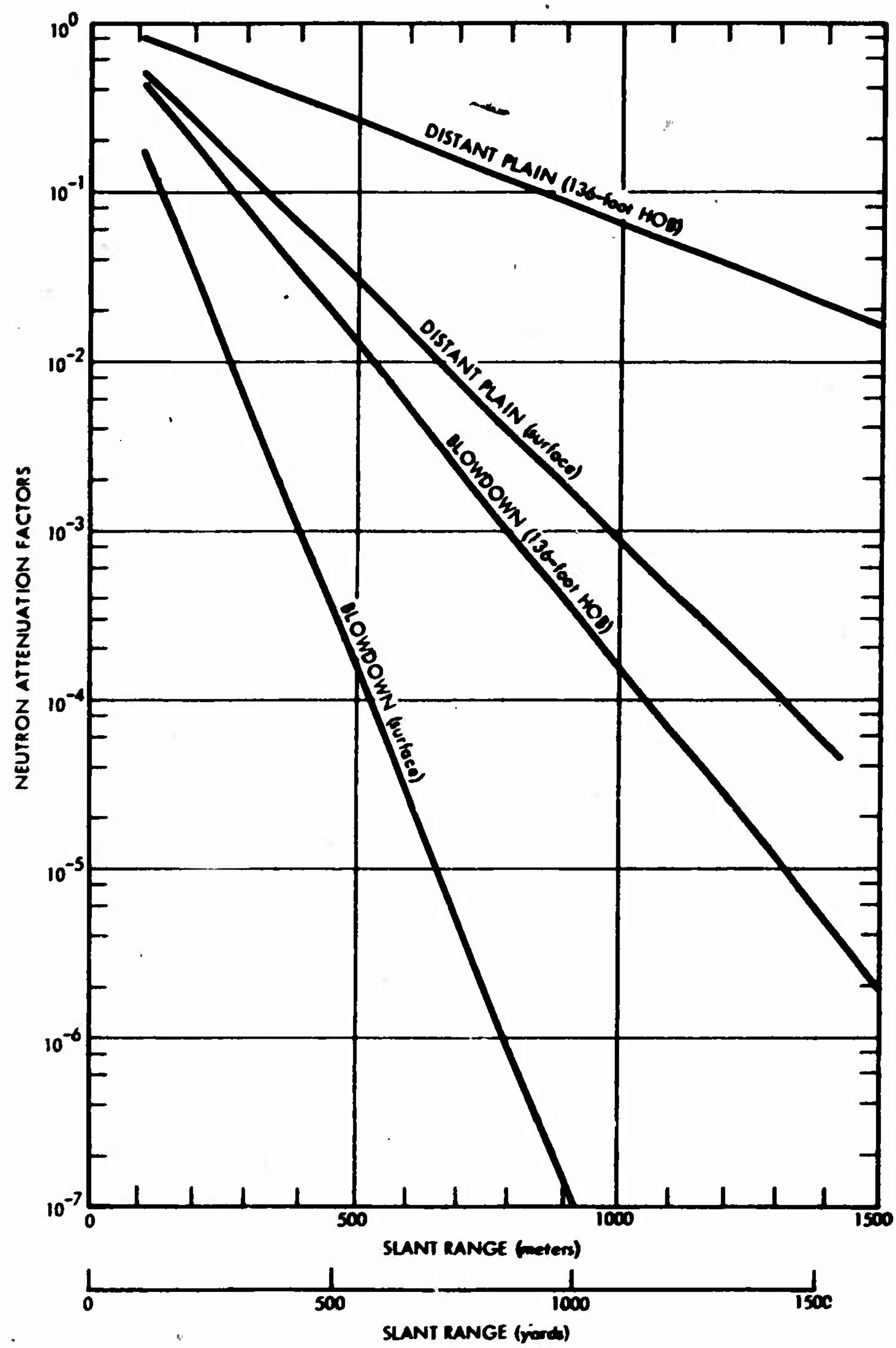

Figure 5-8. Neutron attenuation factors for the Distant Plain coniferous forest and the Blowdown rain forest.

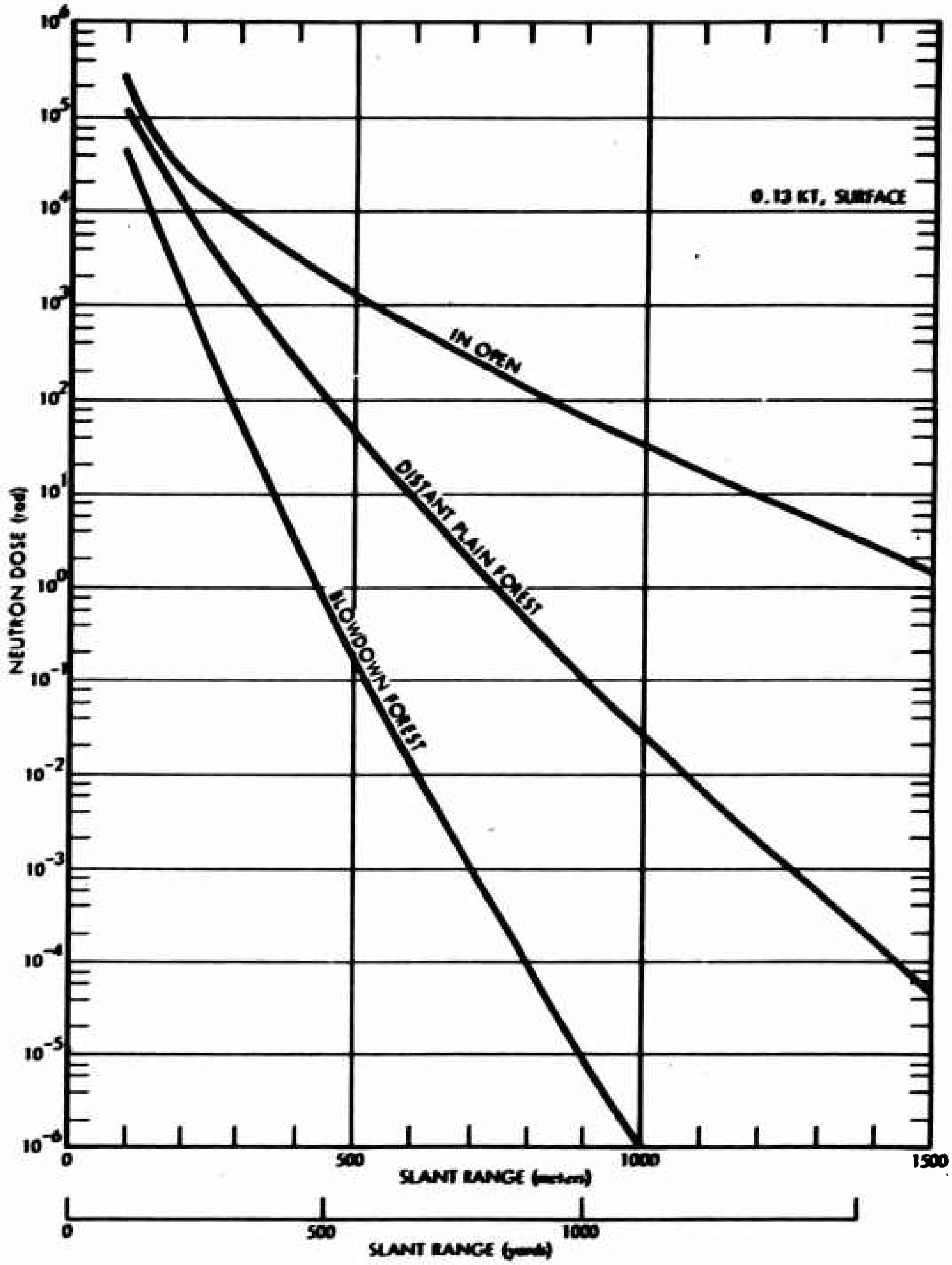

Figure 5-9. Neutron dose versus slant range for a 0.13-KT surface burst in the Distant Plain coniferous forest and the Blowdown rain forest.

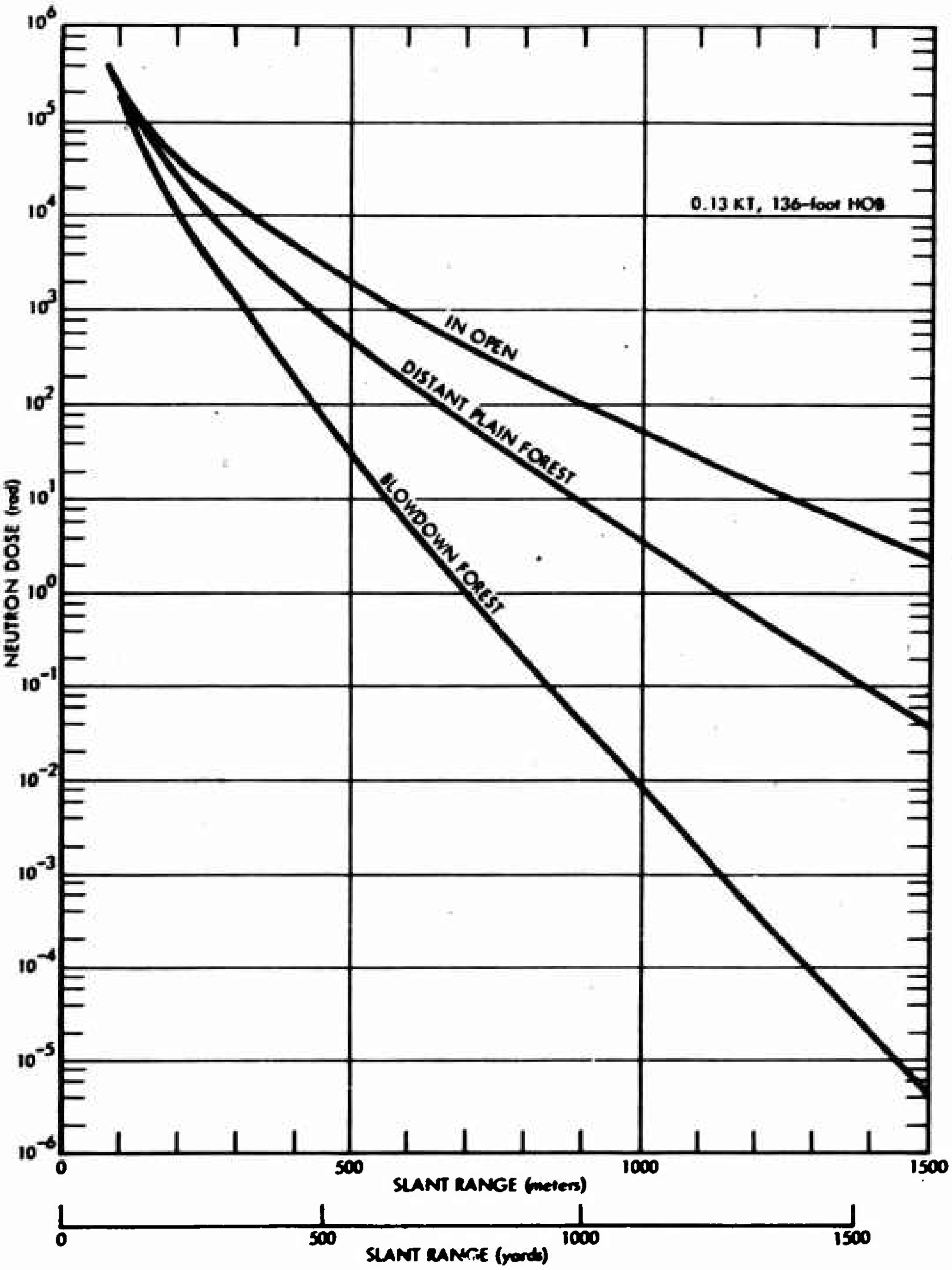

Figure 5-10. Neutron dose versus slant range for 0.13-KT at 136 feet height of burst in the Distant Plain coniferous forest and the Blowdown rain forest.

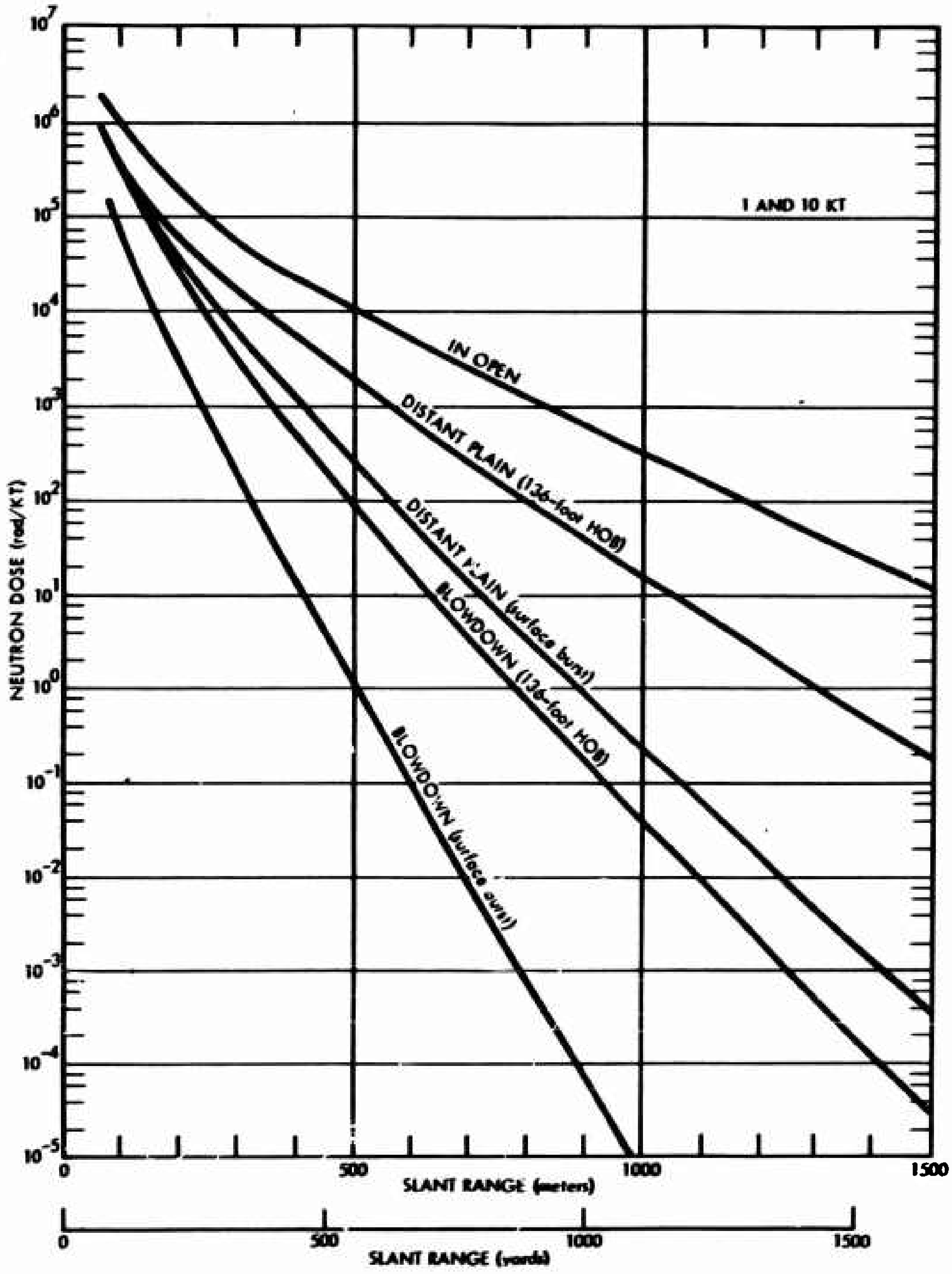

Figure 5-11. Neutron dose versus slant range for the Distant Plain coniferous forest and the Blowdown rain forest in rad/KT for 1- and 10-KT yields.

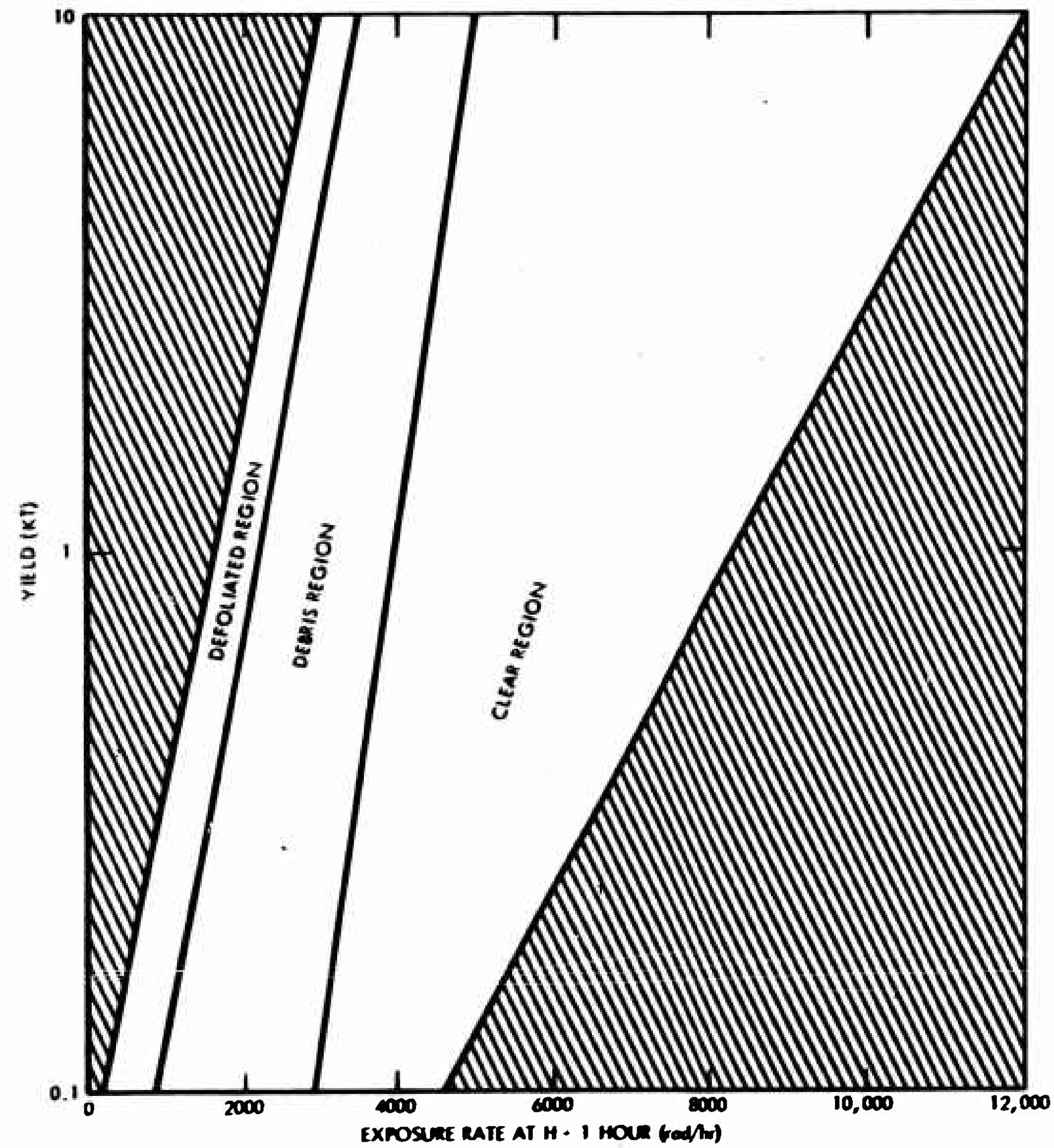

Figure 5-12. Smooth-plane residual gamma exposure rates in the downwind sector of the blast damage area.

Table 5-1. **Forest damage from nuclear explosions.**

EFFECT	Radius of Effect (ft)		
	0.13 KT	1.0 KT	10 KT
Clear Region	100	200	430
Debris Region	500	1200	4000
Defoliated Region	800	2000	6000

roughness effect due to the presence of debris. The degree of reduction for this extreme case of ground-roughness cannot be properly assessed without a fairly extensive theoretical or experimental effort. The fallout can be assumed to be deposited on the fallen stems, on the ground between them, and on any remaining foliage. The position of the detector would play an important part. Adjacent stems would provide shielding from the fallout located at points beyond the stems. At the same time, fallout deposited on stems and foliage at waist height with respect to a man standing on the ground should contribute to the exposure otherwise received. A man walking on the stems would be exposed to a still different source geometry. In any event, the overall gamma exposure rate should be less than that for the smooth-plane situation." Typical reduction factors are 0.7 to 0.8 for turf or bare ground and 0.5 for a plowed field with 6-inch-deep furrows.

AREA UNDAMAGED BY BLAST. The retention of particles by foliage was extensively studied during the eruption of the Costa Rican volcano Irazu. The observed deposition mechanism of the volcanic ash-sand was that of gravitational settling on plant surfaces. The size distribution of the material retained on plant surfaces was generally the same as that on the ground, and the deposition rates were within the range characteristic of close-in fallout. Calculations indicate that for the forest case, the surface area available is sufficient for temporary retention of 100 percent of the arriving fallout. The main effect of retention is the delivery of a beta dose to the foliage; in many cases, especially for deciduous trees, this causes defoliation but not death. The half-life for retention of dry material is reported as 2 to 6 hours over a range of winds from 3 to 16 miles per hour. Humid conditions will increase original retention by a factor of 2. Removal by rain (0.4 inch) is nearly complete, redepositing the fallout on the ground.

GENERAL PROCEDURE FOR CALCULATING FALLOUT EXPOSURE RATES WITHIN THE FOREST. The reduction of exposure in a forest compared with that in the smooth plane situation is provided by the results of analysis using the TERF computer code (Reference 6).

Three forest types were investigated, each being represented by a homogeneous cylindrical region 1000 feet in diameter. Two of these problems were also rerun with a 100-foot diameter clearing inserted in the middle of the forest. In each case the detector was 3 feet above ground on the axis of the cylinder. Figure 5-13 specifies for each case the geometry, material density, and the percentage of arriving fallout (i.e., fallout retention factor R_f). The fraction retained was distributed uniformly with height in the trees, while the remainder settled to the ground surface. It should be mentioned that the forest region was actually a mixture of foliar material and full density air. This is justified since the foliage in typical forests displaces only a small fraction of the total volume of air in the forest. The given material densities therefore include 0.00122 gram per cubic centimeter of air. Also worth noting is the fact that only the tree canopies (leaves and branches) have been represented in these problems. Neglecting the tree trunks accounts for the appearance of the forest as being "suspended" in air. As has often been shown in radiation transport calculations, a significant overestimate of gamma-ray scattering results from approximating a few widely separated scatterers by a homogeneous mass containing the same amount of material It is a better approximation to ignore these local scattering points (tree trunks) entirely.

The calculated results are shown in Figure 5-14 where relative exposure is plotted against material density. Note that on the horizontal scale "0" is an open area and "6" is a very dense forest with large trees. These case studies involved numerous variables including tree height, fallout retention factor, and relative abundance of each chemical element in the forest, so that this curve does not tell the complete story. However, total density appears to be the most meaningful independent variable for plotting the exposure.

For cases containing no central clearing, the results indicate that the total exposure is very nearly inversely proportional to the density. Assuming that the fallout retention factor goes to 0 as the density approaches that of air, the lower curve should depart from this linear relationship at low densities and extrapolate to 1.0 at about 1.2 mg/cm^3. No calculation was done for low density trees with a clearing since it was obvious from the data that this problem would give a relative dose very close to 1.0.

FOREST TYPE	DENSITY (gm/cc)	H_t (ft)	H_c (ft)	RF (%)
Low density	.00203	20	16	35
Medium density	.00540	40	32	60
High density	.0141	40	32	90

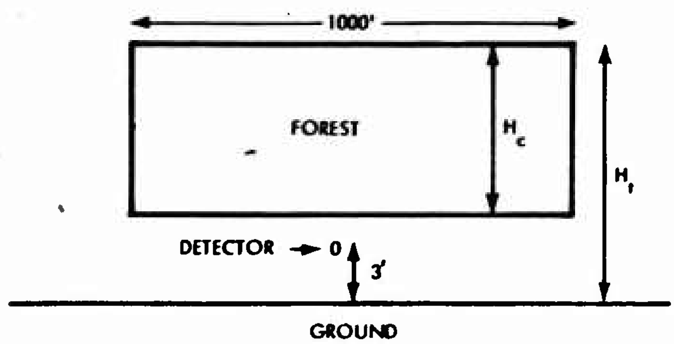

Figure 5-13. Definition of forest parameters.

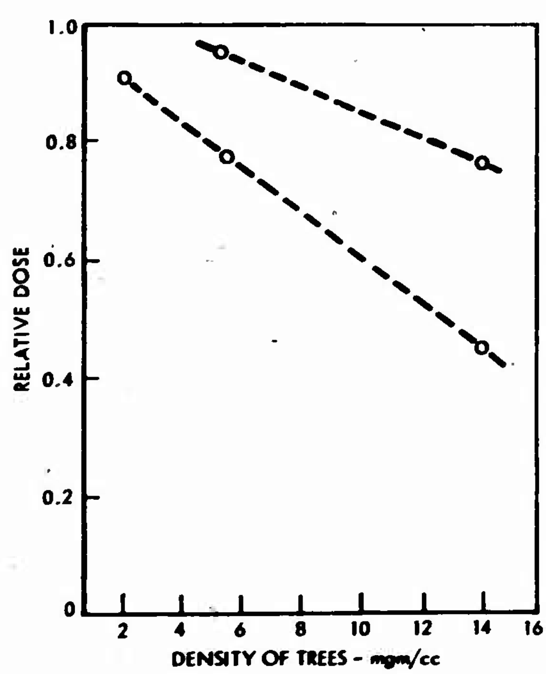

Figure 5-14. Exposure calculations in forests.

5.3 AIR BLAST

The magnitude of the effects of air blast on tree stands is dependent on the dynamic structural response characteristics of the trees, branches and foliage, and on the characteristics of the blast waves. Trees are drag-sensitive structures responding essentially to the blast winds behind the shock front, and the response is thus quite sensitive to weapon yield. There are three primary areas of interest associated with the interaction of air blast with tree stands. These are:

1. The estimation of the degree of damage which is likely to be suffered by a particular forest or fruit-bearing tree stand

2. The implications of the wind-translated forest debris on field troops and civil defense operations

3. The forecasting of fire conditions in a forest seriously disrupted by blast effects.

References 1, 2, 4 and 5 represent the early work done in the area of blast effects on tree stands.

5.3.1 Damage to Forests

Air blast damage to trees, in order of increasing severity, is generally in the form of removal of foliage, breakage and removal of branches (crown breakage in the case of deciduous trees), and breakage of the trunk or stump and uprooting. Damage to forests has been found to correlate with tree size, type, and density and the growing conditions associated with the wooded area.

Forest vulnerability categories are listed in Table 5-2. Vulnerability of each of these categories to air blast is presented in the form of isodamage height-of-burst charts using light, moderate, severe, and total as damage descriptors. These descriptors are further defined in terms of percent of crown breakage or length of stem down per acre, and percent of blowdown as tabulated in Table 5-3. (See Reference 2.)

It should be noted that these descriptors do not pertain to any one particular average tree, but indicate damage to a population of trees. This agrees with observations of damage to forested areas by wind storms as well as from nuclear tests in that the number of trees blown down correlates with the severity of the windstorm or the magnitude of the drag overpressure and duration; whether a particular tree will

Table 5-2. Forest vulnerability categories.

Type	Description
1	Conifer—improved
2	Conifer—unimproved—unfavorable growing conditions
3	Conifer—unimproved—favorable growing conditions
4	Deciduous—temperature zone (like cloud forest - above 3,500 ft elevations)
4a	Type 4—defoliated
5	Deciduous—rainforest—very dense
5a	Type 5—defoliated
6	Deciduous—temperature zone scattered—also orchards
6a	Type 6—defoliated
7	Rubber plantation—very little underbrush and dense overlapping crowns

Table 5-3. Percent of blowdown and crown breakage, or length of stem down per acre. (Adapted from Reference 2.)

Damage	Conifer	Deciduous
Light	Not used	50 percent crown breakage
Moderate	1,500 ft of stem down/acre	750 ft of stem down/acre
Severe	9,000 ft of stem down/acre	7,500 ft of stem down/acre
Total	Over 90 percent blowdown	Over 90 percent blowdown

be blown down cannot be predicted. Root structure has been observed to be significant. Field data further confirm that little pressure attenuation due to tree interference can be anticipated as the blast wave passes through the forest.

The reduction of these data to a common base (the percentage of tree breakage or blowdown in a forest stand or orchard) required converting length of stem down per acre to percentage of stems down through use of average tree heights and densities for the forest types represented. The data in this form were used in Reference 7 to construct the composite tree debris chart, Figure 5-15, relating percent of debris to overpressure for the various types of forest.

Figure 5-15 reflects the percentage by volume of a particular forest stand or orchard converted to debris as a result of branch and stem breakage or blowdown. In its construction, cognizance was taken of statistical differences of the trees in the particular forest stand (size, shape, strength, fundamental frequencies, rot, knots, roots, fire scars, etc.) and as a consequence it should be applied to a group of trees, such as a forest stand or orchard (instead of a single tree or average tree), where the tree population is sufficient to encompass and represent average statistical differences. Note that because Figure 5-15 shows only 5 MT weapon effects, scaling to other yields should take into account dynamic wind factors and their variations with yield.

5.3.2 Translation of Forest Debris

The point at which a given fragment of forest debris finally comes to rest depends upon the drag characteristics of the fragment, forest density, the initial height above ground, and the yield of the weapon for cases of high overpressure. Below about 2.5 psi the stems of trees remain standing and offer considerable interference to the flight of branches.

Tree debris may constitute a hazard to personnel, may contribute significantly to the disruption of electrical power distribution systems and substations and radically alter the fuel bed in a forest subjected to both blast and fire. Theoretical free trajectories for branches falling without interference after being dislodged from various heights are shown in Figure 5-16 for two weapon yields. These plots can be used to estimate various potential damage ranges or distributions of the forest debris at different overpressure levels.

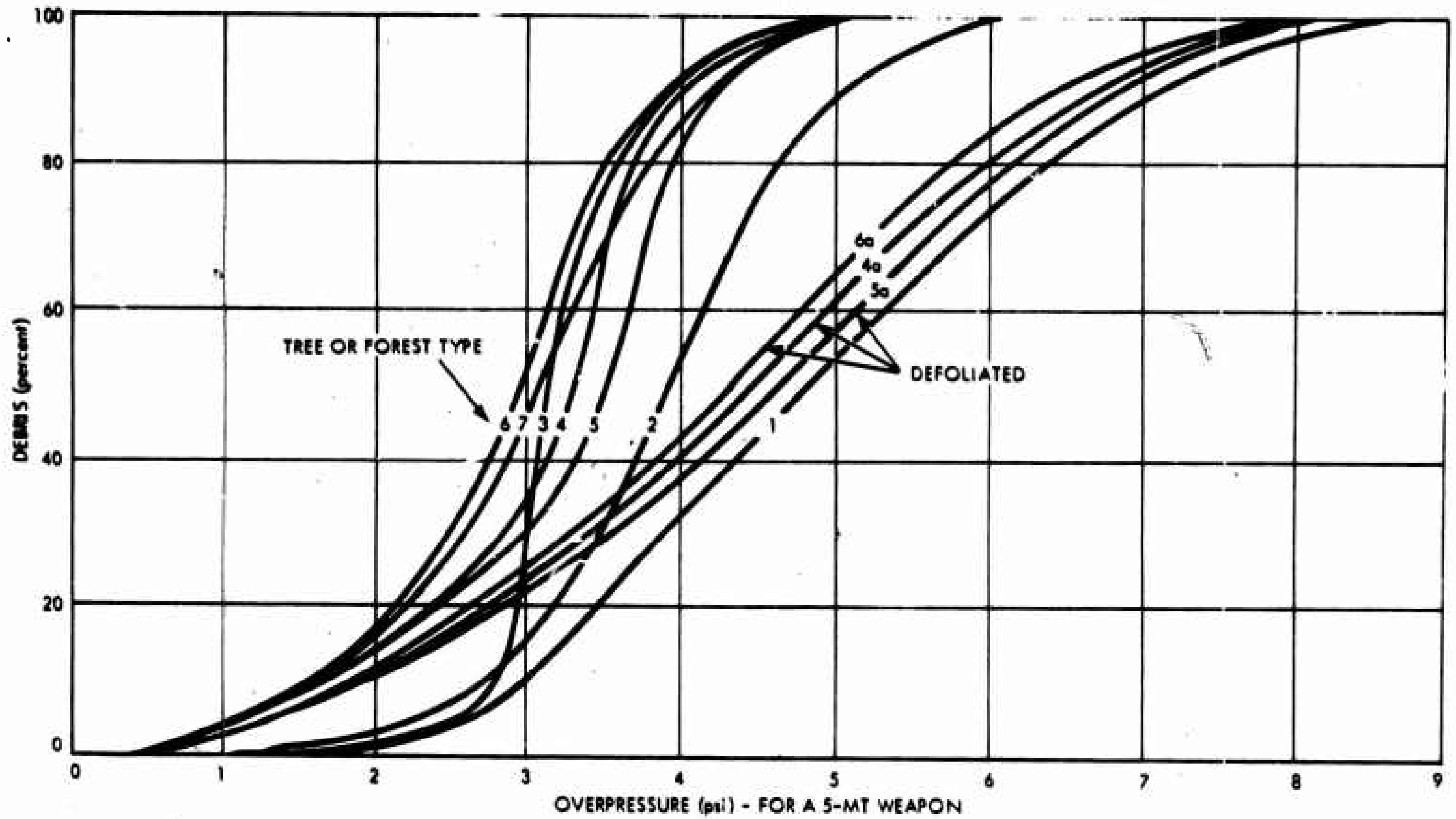

Figure 5-15. Tree debris chart.

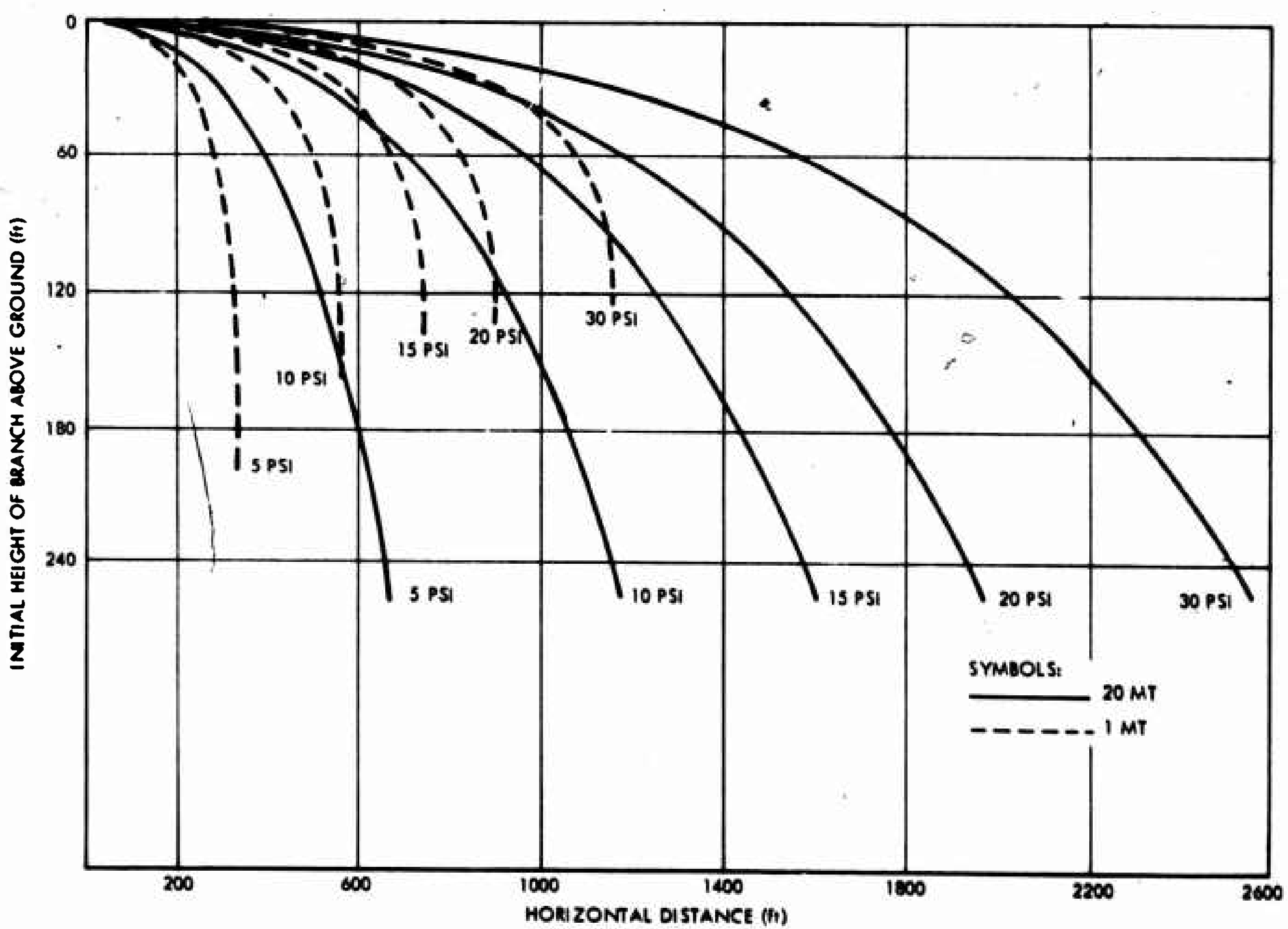

Figure 5-16. Branch trajectories during the positive phase of a nuclear blast.

5.4 INFLUENCE OF FORESTS ON GROUND SHOCK

Ground shock produced by nuclear or high-explosive bursts can be categorized as follows:

1. Directly induced ground shock - emanating from the detonation of a device or weapon near, at, or below the surface of the earth, whereby some portion of the explosive energy is directly coupled to the earth through cratering action.

2. Air blast-induced ground shock produced by the air blast wave emanating from the detonation of a device or weapon above, at, or slightly beneath the surface of the earth, whereby some portion of the explosion energy is indirectly coupled to the earth.

The principal weapon variable determining the influence of forests on ground shock development is the height of burst. A forest has no effect on a deeply buried (fully contained) burst, and only minimal effects on shock and blast from bursts high above the surface.

For surface or near-surface detonations where both types of motion are present, the directly induced ground motion is known to be the dominant motion in the vicinity of the crater. These motions attenuate more rapidly with distance than the air blast motion and beyond a few crater radii they tend to become insignificant in relation to the air blast-induced motions; see Figure 5-17.

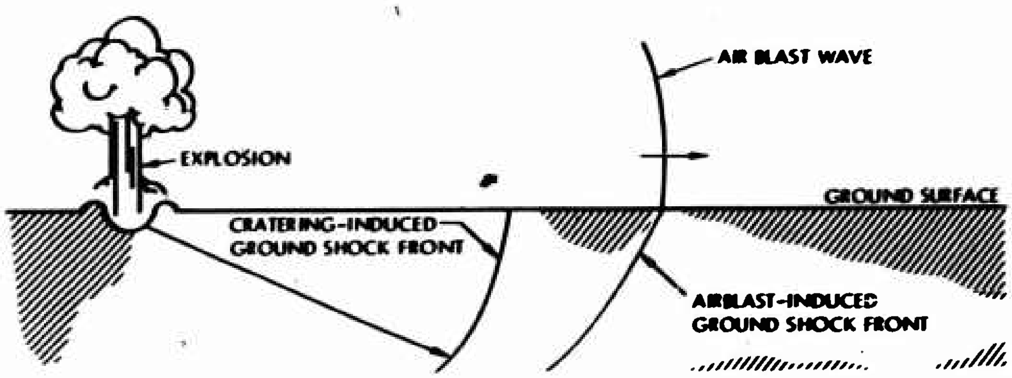

Figure 5-17. Schematic of crater- and air blast-induced ground motions.

When the direct induced motion or air blast-induced motion arrives at a given point before the air blast, it is said to "outrun" the air blast usually in the case of surface blast. This can arise from the soil seismic velocity being greater than the velocity of sound in the ambient air, or as is often the case, a layering of the soil with a higher velocity layer underlying the surface layer, as shown in Figure 5-18. Directly induced motion and its associated outrunning motion, if it occurs, is characterized by initially upward components of generally much longer rise times and durations than the sharp downward spikes of air blast-induced motion.

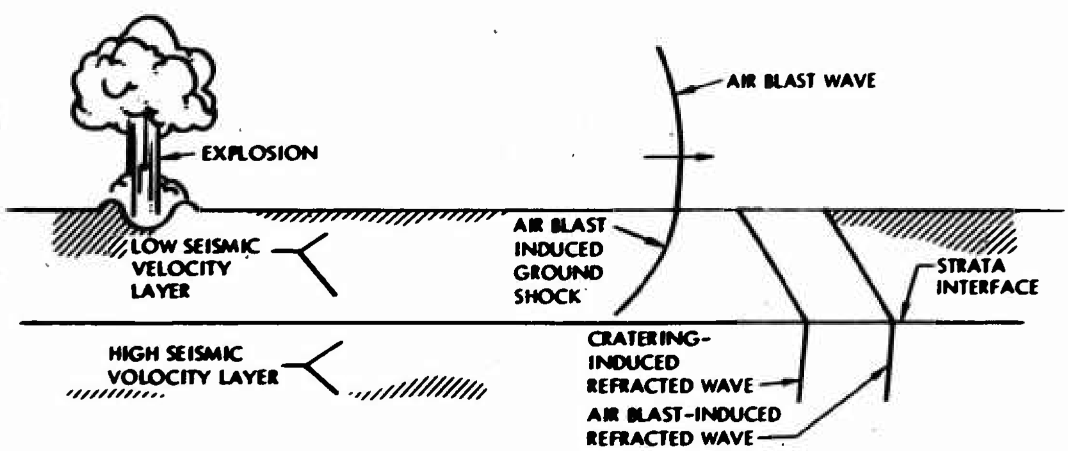

Figure 5-18. Schematic of outrunning ground motion due to layering.

Since it has been shown that an upward moving disturbance can, under the proper conditions, precede the air blast arrival, it is desirable to infer the effects of this motion on the vulnerability of trees to subsequent blowdown. Clearly, the upward moving stress wave would produce a strain or bulge in the near-surface medium. If of significant magnitude, this strain could contribute materially to the blowdown mechanism by causing partial uprooting prior to air blast arrival. Experience has generally shown, however, that displacements in the region of outrunning motion are on the order of a small fraction of a foot with associated stresses and strains correspondingly small. For example, at the Watching Hill blast range of the Defence Research Establishment Suffield (DRES), where nearly ideal outrunning conditions exist, near-surface displacements produced by the upward moving pulse are in the neighborhood of 0.1 inch. It is improbable that motions of this magnitude would be significant in tree blowdown.

Air blast-induced ground motions at the Nevada Test Site were determined to be approximately proportional to the peak air blast overpressure directly above the point in question. These relationships were determined from both empirical analyses and empirically modified theoretical analyses and were found to be adequate representations for pressure less than about 500 psi. These relationships usually were expressed as ratios of motion to overpressure (g/psi or ft/sec/psi) Reference 7, or empirically modified one-dimensional theory as in Reference 8. For example Sauer (Reference 7) estimates vertical accelerations and velocities at a 5-foot depth at Frenchman Flat to be 0.45 ± 0.15 g/psi and 0.5 ± 0.1 ft/sec/psi, respectively, and Newmark (Reference 8) gives this expression to estimate particle velocity:

$$\mu = 4 \left(\frac{P_{so}}{100}\right) \left(\frac{1000}{c}\right) \alpha_Z$$

where

P_{so} = peak overpressure at ground surface

μ = particle velocity (peak)

c = compressional wave velocity

α_Z = depth attenuation factor

An early indication of the importance of the air blast wave shape was noted for Priscilla and Tumbler Shot 4 (Dog) events where precursor waveforms, with increased rise times, produced decreasing ratios of motion to overpressure. This experimental evidence suggests that a forest-perturbed air blast wave, having a finitely longer rise time, will generate smaller accelerations than a classical blast wave, perhaps by a significant amount. The effects on particle velocity would tend to be less pronounced. Drag-sensitive objects, such as trees, are naturally vulnerable to precursor effects.

More recently, theoretical studies of the response of various soil models to air blast loadings have brought to light the importance of the rate of decay, or relaxation time, of the pressure pulse. In general, a rapid decay of the peak pressure, which may be associated with high pressures and/or low yields, will tend to be inefficient in producing ground motion at depths a few feet below the surface. The effect of this is that motion to pressure ratios, although essentially constant at lower pressure, have a tendency to drop off at higher pressures for a given weapon yield. For example, on Distant Plain, Event 6, ground motions showed only a factor of 2 attenuation between 2,000 psi and 300 psi, but dropped off rapidly beyond this point with an attenuation factor of about 8 between 300 psi and 50 psi. This latter rate of attenuation more nearly approximates the linear variation with overpressure mentioned previously.

The perturbing influence of a forest would probably be less on the decay-duration characteristics of the air blast than they would on the normally discontinuous pressure rise. Thus, though any perturbations on the rise and decay of the air blast waveforms would have generally opposite effects, it is felt that the effects produced by the disturbed rise time would predominate and, other factors being equal (soil types, yield, etc.), air blast-induced motions would be less in a forested environment.

During Operation Distant Plain, Event 4, ground motions were measured along two radial lines from ground zero, one line being in a forested environment and the other being in a cleared sector. Although measurements were successfully made at nearly all instrumented locations, results were generally inconclusive as to the effect of the forest (Reference 9). Measurements at a depth of 5 feet did show a reduction of motion in the forested sector by a factor of about 2. However, measurements at a depth of 1.5 feet showed some scatter such that at one point the forest measurement was the larger while at the other the cleared sector produced larger motion.

In general, then, it can be stated that the small amount of empirical data gathered to date are insufficient to allow forest effects on ground motion to be predicted with any degree of confidence. However, since the dependence of ground motion on the shape of an air blast wave has been verified both empirically and theoretically, it is reasonable to conjecture that the primary influence on the blast effect by a forest should arise from perturbation of this wave shape. It is suggested that any such perturbations would tend to attenuate motions, with the effects on accelerations being greater than those on particle velocities.

5.5 BLAST-FIRE INTERACTION

The blast wave can influence fire development and spread in three ways. First, the blast wind can extinguish some initial ignitions, and "fan" others into greater activity. This is not a major factor in a forest environment. Second, the blast damage to some sources of combustion may add ignition points, over and above those due to the thermal pulse. This is a negligible factor in a forest environment, though important in the urban situation. Finally, the blast wave rearranges the fuel bed during delivery of the thermal pulse and before fire buildup. This is an extremely important factor in all situations especially for multiple bursts.

5.5.1 Rearranged Fuel Beds

This topic is discussed in greater detail in Chapters 4 and 9. The most important factors are the following:

1. Removal of the forest canopy can expose forest litter to the thermal pulse close-in to high yield weapons.
2. Burning debris can be translated to unignited areas.
3. Burning characteristics of stripped tree trunks and great expanses of broken-off branches are very different from those of the original standing trees.

5.6 FIRE-FALLOUT INTERACTION

There are two cases of interest in this area. First is the effect of fire moving through an area already covered with fallout. Next is the effect of a going fire on an arriving fallout cloud.

5.6.1 Fire Removal of Fallout

Limited tests involving radioactive tracers have been made in connection with several experimental fires. In all cases the turbulent air movements associated with the fires redistributed the radioactive materials in very local areas and did not redistribute them down wind. No quantitative data are available, but the overall effect is one of reducing levels of contamination in portions of the fire area and increasing the down rate elsewhere in the same area. This happens often because the fire destroys shielding objects.

Operationally, this means that if fallout is already known to be on the ground in the fire area, there is a probable alteration to the hazard pattern. Decisions on use of such an area must of course be based on monitoring reports.

5.6.2 Convection Column Influence on Fallout

A strongly developed convection column creates a discontinuity in the airflow pattern in its vicinity. It thereby prevents deposition of fallout in the fire area and causes heavier concentrations farther downwind. The violent turbulence often associated with fires can lead to irregular concentrations of fallout in the adjacent areas. Once again the need for monitoring is apparent.

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CHAPTER 6

VEGETATION AND THERMAL IGNITION EFFECTS

6.1 COMPARISON OF BLOWDOWN AND THERMAL CRITERIA

6.1.1 Definition of a Forest

For blowdown purposes a forest can normally be defined as a dense growth of trees with or without undergrowth covering a relatively large area. The forest may have military significance from the standpoint of trafficability to tracked vehicles or for the cover it provides for personnel or materiel (Reference 1). In the first case the trees must be tall enough, large enough in diameter, and of sufficient density in terms of trees per acre that blowdown will affect such trafficability, while in the second case smaller diameters, heights and densities may suffice.

Forests from a thermal standpoint must be defined somewhat more broadly. In this case, nonforest flammable vegetation which, by supporting fire either with or without a blowdown, may affect military operations. Such vegetation by initiating fire may also provide the fuse for igniting a contiguous forest.

6.1.2 Blowdown Criteria

Forest blowdown is estimated on the basis of forest tree response to blast wave loading force following a nuclear detonation. Chapter 5 indicates how world forest types have been classified with respect to the degree of tree breakage, defoliation and translation of damage debris. It also relates these effects to weapon yield. The accompanying data permit estimates of the horizontal ranges of a limited number of degrees of damage severity. The limits of error have not been determined, but we must assume at this time that they are small enough to allow practical applications for military purposes.

6.1.3 Thermal Criteria

Forest thermal effects must be estimated on the basis of two very different forest characteristics: the ignition potentials of forest and other vegetation, and the fire behavior potential of the associated vegetation in terms of rate of spread, fire intensity, and crowning probability. Both of these fire characteristics depend upon:

1. Availability and distribution of ignitable tinder fuels.
2. Availability and amount of burnable surface kindling* and larger fuels.
3. Species, associations, and their relative flammabilities.
4. Horizontal vegetation cover density.
5. Relative amounts of live and dead fuel.
6. Vertical structure including undergrowth.
7. Character of the vegetation as it affects microweather.

This chapter is concerned primarily with ignition potential. Nevertheless, it is desirable here to consider the other forest flammability characteristics as a basis for formal characterization of forest types in Chapter 7 and discussion of fire spread in Chapter 9.

Forest blowdown in an ignited area can modify subsequent fire behavior. In areas of various degrees of blowdown tree canopies will be added to the fuel on the forest floor. The distribution may be more or less uniform or the blow-down fuels may be concentrated in various dispersions and concentrations depending on height of burst, the nature of the forest, and the severity of damage. At the far limits of blowdown and beyond there may be various degrees of defoliation which merely add leaves, needles, and twigs to the surface fuels. In most conifer forests flammable, defoliated material adds measureably to the volume of immediately burnable fuel. Less is known about the effects of broadleaf blowdown or defoliation, but due to the generally lower flammability of tropical broadleaf trees and deciduous broadleaves, the probable effect may be one of suppressing fire spread until considerable drying has taken place.

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* Kindling fuels are those generally larger or thicker than tinder, but are ignitable by burning tinder and provide the bridge between sustained ignition and fire spread.

The predictability of thermal effects with respect to fire ignition has been reasonably well established through exposure of natural tinder fuels to both weapons tests and laboratory work on the various thermal characteristics of several fuels. The only fuel inputs necessary are a knowledge of the physical and chemical properties of the ignitable fuels involved and their approximate moisture contents.

6.2 BLOWDOWN TYPES vs. FUEL TYPES

Based on the above different criteria, it appears desirable to distinguish between forest blowdown types and fuel types even though one includes the other. Another reason for the distinction is that forest types associated with different climatic regions have quite different fuel and weather-controlled flammability relations.

6.2.1 Fuel Types

A forest fuel type is defined as the total living and dead vegetation that occupies a distinctive geographic area, part of all of which may be burnable. This definition makes it desirable to establish a compromise for fuel types between the designated blowdown types and a modification of the world's 15 classical vegetation types set forth by Dansereau (1952) (Reference 2).

The broad vegetation types selected for fuel description purposes and their associated climatic types are listed in Chapter 7. Because these types are broad, overlap, and contain many sub-types, it appears germaine at this point to briefly consider the particular kinds of fuels susceptible to ignition by the radiant thermal pulse. Some of them may be found in various combinations in more than one fuel type.

Among the more common wildland materials meeting the ignition requirements and recognized as tinder are:

1. Dry grasses and sedges
2. Lichens and mosses
3. Dead coniferous needles
4. Dead broadleaf leaves
5. Bark of certain tree species
6. Rotten wood (punk)
7. Organic soil

8. Dry plant fruiting bodies

9. Animal droppings

All of these may differ in their susceptibilities to ignition primarily because of their physical dimensions, thermal characteristics, and weather-controlled moisture contents as well because of chemical differences (References 3, 4, 5). The chemical differences, as yet, are not well defined for all fuels.

6.3 INTERACTION OF LIVING VEGETATION WITH THERMAL PULSE

6.3.1 Thermal Reactions

Only living foliage is considered in this case because the insulating bark of branches and stems will ordinarily protect these materials from the immediate effects of thermal radiation. The phenomena which may occur in the foliage are:

1. Complete incineration of the foliage within, or in close proximity to the fireball from surface and low altitude bursts.

2. Explosive dehydration through the rapid vaporization of contained moisture which quickly condenses into a cloud of steam which, in turn, may have some effect on thermal shielding.

3. A slower dehydration of the foliage at longer pulse lengths and lower intensities with approximately the same drying.

Foliage is generally killed if its temperature reaches approximately 140° F. Although the dehydrated or killed foliage may not ignite during the pulse, it may supply some additional fuel for later fire behavior originating from other ignitable fuels. The most important feature of this is that living foliage will not ignite and burn as an ignition source.

6.3.2 Screen Effects

Trees and lesser vegetation in foliage effectively shade materials beneath or behind the surface foliage layer from thermal radiation from a fireball. This information is derived from two Nevada weapons tests observations. At Operation TUMBLER-SNAPPER (Reference 6) several rows of spaced Ponderosa Pine trees were placed at varying distances from ground zero. Strips of wood placed behind one very open crowned tree were not charred by 22 calories per cm^2 delivered by a 45-KT weapon. Similar strips exposed nearby in the open with full exposure to the fireball were heavily charred. Post-shot observation also disclosed that only the edges of the tree crowns facing the fireball had turned gray-brown in color while the needles on the interior and backsides of the trees showed no signs of desiccation. This same phenomenon of only surface needle dehydration facing the fireball was observed on Operation UPSHOT-KNOTHOLE (Reference 7). In both of these events high speed motion pictures showed an almost instantaneous burst of steam arising from the tree crowns. It must be assumed that this also had some effect on attenuation of the thermal radiation, although there is no conclusive evidence of this. Even though the evidence is sparse, nevertheless it must be concluded that only a thin living foliage cover is necessary to effectively shade otherwise ignitable fuels beneath at any level of exposure that does not actually consume the shielding foliage. An important exception to the screening effect of living foliage may occur in the case of high yield weapons at close-in distances where forest blowdown or defoliation may precede a major part of the effective thermal pulse.

Broadleaf vegetation not in leaf is somewhat less effective in screening surface fuels than are those trees which are in leaf. There are no test results to support this conclusion but intensive inspection of West German broadleaf forests not in leaf from both air and ground observations led the Forest Service to conclude that more, larger holes appear in the canopy than in forests when in leaf. See Section 6.4.3 for further elaboration.

6.4 EXPOSURE OF TINDER FUELS

6.4.1 General

Fuels susceptible to ignition by nuclear radiation at reasonable amounts and intensities are, for the most part, limited to those listed above. This is not an exclusive list, but incorporates the most frequently found susceptible fuels in wildland situations. Other dead materials may exhibit transient flaming during the period of the pulse but go out as soon as the incoming radiation ceases.

6.4.2 Ignitable Fuels Aloft

Ignitable fuels often found in the upper forest canopy for the most part consist of the two classes — rotten wood and draped lichens. Virtually all conifer forests from middle age to maturity, except those under the most intensive management, contain a few to many dead trees or living trees with dead tops. This dead material often occurs at or above the general level of the canopy in various stages of decay, but usually with a high proportion in the form of punk. The branches of broadleaf trees even in managed forests also frequently die and are susceptible to the same processes of decay. However, broadleaf trees in leaf, usually shield these branches from significant thermal radiation; consequently, in these trees ignition will be at a minimum. In broadleaf deciduous forests in the temperate region, much of this deadwood will be exposed to direct thermal radiation when the trees are not in leaf. In humid tropic regions deadwood does not persist for any appreciable time because of the extremely rapid rates of decay and even the semideciduous forests of these regions rarely contain appreciable quantities of decayed wood aloft. Ignited deadwood in the tree canopy usually becomes a spreading fire source only after it has fallen to the ground to ignite surface litter.

Draped lichens aloft are typical of only certain restricted forest regions. The Northern Boreal forest is one of these. Here, over relatively large areas, nearly every spruce and fir tree crown is sheathed in a mantle of these materials which are highly flammable when dry. Observations of forest wildfires in these forest stands show that the lichens are usually the first materials ignited after which the whole tree crown immediately goes up in flames. A similar lichen known as Spanish Moss occurs on the evergreen live oaks of the subhumid southern and southeastern United States. Here the tree crowns may also be ignited while at the same time burning embers are dropped to the ground.

Some deciduous broadleaf trees retain their dead leaves until the following growing season. It is not known whether or not these leaves constitute potential kindling fuels, but if they do, each ignited leaf probably serves as an individual ignition point. Mass crowning can generally be expected to be minimal.

6.4.3 Ignitable Surface Fuels

Surface fuels susceptible to fireball ignition include all those listed above in both forest and nonforest types. Live vegetation shielding, however, including potential steam shielding, limits direct ignition of fuels on the surface to:

1. Nonforest types such as dry grass, tundra or nonforest litter.

2. Forest edges wherever the tree canopy is high enough for the fireball to be visible from beneath which may occur in both coniferous and broadleaf forest stands. When trees are in leaf this is usually limited to a relatively short distance within the stand because of the increasing shading by the tree stems with depth into the forest. This is usually increased somewhat in broadleaf stands when the trees are bare.

3. Forest openings either natural or man made in which tinder fuels may occur. In the later case, problems of the geometry of the forest and of the fireball become important with respect to the forest tree height, size of openings, and the possible generation of steam cloud appear the most important. These are modified to an appreciable extent in broadleaf forests according to whether the trees are in leaf or not in leaf.

When broadleaf trees are in leaf the sizes of openings in particular appear to be minimal and the possible generation of steam clouds is at a maximum. One of the reasons for this apparent minimal size of opening when trees are in leaf is that openings in the taller tree canopy are often filled with young broadleaf reproduction or other green vegetation which effectively shades the surface fuels. The Forest Service observed in western Germany (Reference 8) that when the trees are not in leaf, holes in the tree canopy appear larger and, because of their small stems and small as well as sparse branches, the young reproducing broadleafs did not appear to have any significant screening effect on the surface fuels. It was to these openings more than to average shading in an idealized forest that the following estimates were generated by the Forest Service:*

Altitude Burst (degrees)	Full Energy at Surface (percent)
90	95
60	80
45	60
30	25

* These estimates should be compared with those described for a "Standard Northern European Forest" in Chapter 3.

The above estimates were made for a small but finite apparent size of fireball. For other situations other fireball parameters become of increasing importance; among these are pulse duration, rate of fireball ascent, apparent size of fireball, and slant angle. Also important is a fireball shape factor. Most of the standard radiation measurements taken at weapons test sites have determined the nuclear radiation integrated over the area of the spherical fireball considered as a flat plate, thus not distinguishing between point source versus area source of the transmitted thermal energy. It is questionable whether these intensity measurements can be applied over the whole apparent area of the fireball. This may be more an academic question than an operational one because, in most instances, the field values of the needed parameters will usually be unknown. To be conservative the above estimates should also include the increased exposure of dead wood aloft.

6.5 TRANSLATION OF KINDLED FUELS

6.5.1 Fuels Originating in the Fireball Region

Dead flammable fuels larger than tinder near the blast point for ground burst or near ground burst detonations may be ignited by the fireball itself. If large enough not to be completely incinerated immediately, this material may be hurled for considerable distances in a still burning condition. The high speed of this translation will wipe out flame from the fuel during its travel but may still permit high intensity combustion by glowing. Such material may again flame when it comes to rest. The source of this deadwood may either be on the surface or in the tree canopies. Most of the other classes of ignitable fuel will be incinerated in place and not be subject to translation in a burning condition.

6.5.2 Ignited Fuels at a Distance from the Source Point

Fuels which are ignited before arrival of a shock wave and are not blown out may remain in place following shock arrival or may be moved in various ways. This must be dealt with in generalities because materials exposed to the fireball radiation in weapons tests have always been anchored in place. Reason tells us, however, that some differences can be expected between fuel types. Most dead grasses and herbs, for example, are anchored in place by their root systems and may, therefore, be flattened but not moved anywhere. Forest litter, on the other hand, may respond with respect to its individual characteristics and to the strength of the blast wave winds. Uncompacted deciduous broadleaf leaves tend to roll freely along the surface with even nominal winds and should be expected to be carried for considerable distances by shock wave winds before burning out. Coniferous needles, on the other hand, tend to mat and intertwine with each other and thus, for the most part, are less susceptible to this type of movement. Rotten wood is usually quite light in relation to its bulk and therefore would be expected to be rolled at least for considerable distances if the way is clear.

6.5.3 Ignited Fuels Aloft

Ignited fuels aloft and particularly rotten wood can be expected to travel the farthest and remain ignited for the longest period of time. Tariffa (Reference 9) reported the results of his analytical and experimental research on the transport and combustion of firebrands. First he considered the upward transport of such brands in the vertical convection column with speeds up to 45 meters per second, random dispersal of the brands from the convection column at various heights and their subsequent forward and down ward paths in the ambient winds. From his work with charcoal in particular, it is concluded that small pieces of ignited punky wood aloft torn loose by the blast can be transported for comparatively long distances and reach the ground while still burning. Other materials because of short burnout time or greater densities will be effective firebrands only at much shorter distances.

6.6 SUMMARY

This largely qualitative chapter indicates that, with the exception of the most simple wildland fuel complexes, the expected pattern of initial thermal ignitions is that of individual spot fire starts rather than mass fire starts. The availability of ignitable fuels is not uniform in most forest types so that even a sizeable opening in a forest stand is not a guarantee that a fire may start. The forest floor is not a flat plane from the standpoint of fuel orientation, so that some potentially ignitable tinder fuels may be ignited while others may not. And too, some persistent ignitions may occur which have no further chance of life because they do not lie in proximity to kindling fuels to which they could translate fire.

Seven forest thermal parameters were listed without attempt to evaluate their specific effects because they all have to be considered together for any situation and any detonation as each may occur. Answers to the questions raised can only be resolved by on-the-ground evaluation of the parameters involved plus weather and their probable effects on the expected frequency of ignition points that meet the ignition requirements described in Chapter 4.

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CHAPTER 7

FOREST AND CLIMATE TYPES

7.1 INTRODUCTION

The purpose of this chapter is to describe in broad terms the major vegetation types of the world and some of the climatic factors that must be considered in evaluating their fire potentials. The discussion here must be general for many reasons. Principal among them, however, are the large numbers of species and structural differences in the broad vegetation types and infinite variety of climates in which each subtype is found (Reference 1). The vegetation types designated as fuel types in Section 7. 3 are listed in order, poleward from the equator. This in itself is more or less a climatic classification, but forest flammability associated with climate and weather is much more complex than this classification suggests.

The climatic factors of primary concern to fire are the wetting and drying and temperature regimes that affect volume of plant growth, dead fuel accumulation and their periodic flammabilities (References 2 and 3). These factors include both seasonal and short-period variations. In some instances it is often apparent from the climatic information analyzed from this standpoint why certain vegetation types occur where they do. In others, it is not. Many natural and man-caused disturbances enter into the determination of today's world vegetation composition and distribution.

7.2 GEOPHYSICAL DETERMINANTS OF FOREST AND CLIMATE TYPES

The earth and sun being oriented as they are, the sun shines more directly downward on the tropic regions than over other parts of the world. Land and water surfaces in the tropics therefore absorb more heat from the solar radiation than do more polar regions with lower angles of incidence of the sun's radiation. This heating in the tropics causes increased surface temperatures over both land and water which in turn heat the overlying air causing it to expand and rise. At the same time, air over the poles is being cooled by the colder land and water surfaces and tends to settle. This difference in heating and cooling causes the depth of the troposphere, that layer of the atmosphere in which most of our weather phenomena take place, to vary in depth from about 12 to 15 miles over the tropics to slightly over 6 miles at the poles. See Figure 7-1.

Because the air is fluid, that air which piles up over the tropics tends to flow downhill poleward while the more dense cool air over the poles tends to return toward the equator to replace that which is rising. However, this otherwise simple circulation is disorganized by the interplay of two factors. The first is the rotation of the earth on its axis and the second is the orbit of the earth about the sun.

The earth rotates on its axis at a rate of 15 degrees per hour. This angular rotation generates a Coriolis or deflecting force in the overlying air. This force is normal to the direction of motion which is to the right in the northern hemisphere and to the left in the southern hemisphere. This results in changes in air direction. These changes in wind direction develop many local pressure gradients in addition to that from north to south and reverse. Thus many high and low pressure systems develop about the world, some of which are semipermanent in their locations and others which are decidedly transient. Thus the troposphere, in its effort to equalize high and low pressures, causes air to flow from high pressure systems to low pressure systems, but neither is this flow in straight lines. The air in high pressure systems in the northern hemisphere rotates in a spiraling-outward-clockwise direction toward the center of the low pressure system. Rotation of the earth also results in daytime heating and nightime cooling of the earth's surface. This causes diurnal changes in air temperature near the surface but ordinarily not to a depth sufficient to influence greatly the general airflow.

Rotation of the earth on its axis also generates oceanic currents in all of the major seas. These also tend to circulate in a clockwise direction in the northern hemisphere and in a counterclockwise direction in the southern hemisphere. These currents are important in that they carry warm ocean water from lower to higher latitudes and tend to regulate the air temperature and resultant pressure systems above them accordingly.

The earth orbits about the sun with its axis of rotation tilted 23-1/2 degrees from the plane of rotation. This causes the sun's trek about the earth to vary from the Tropic of Cancer in the north to the Tropic of Capricorn in the south. Thus, there is a marked change in seasonal

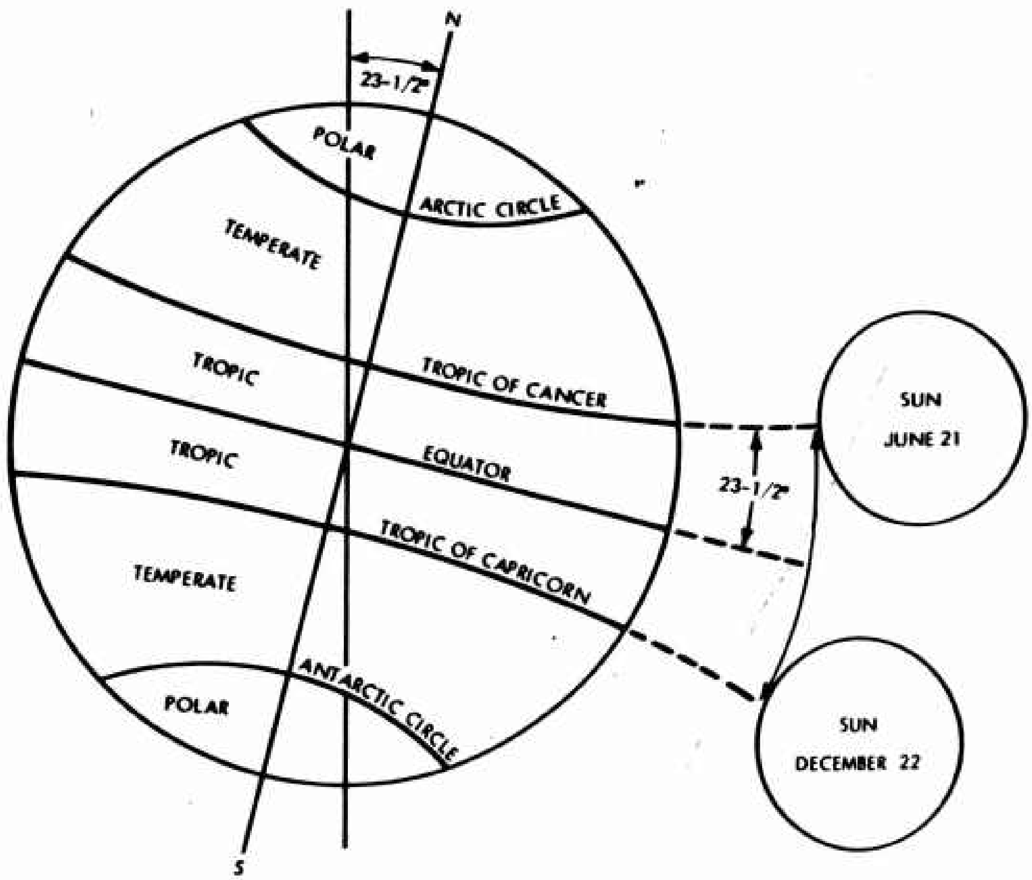


Figure 7-1. The earth and its latitudinal regions.

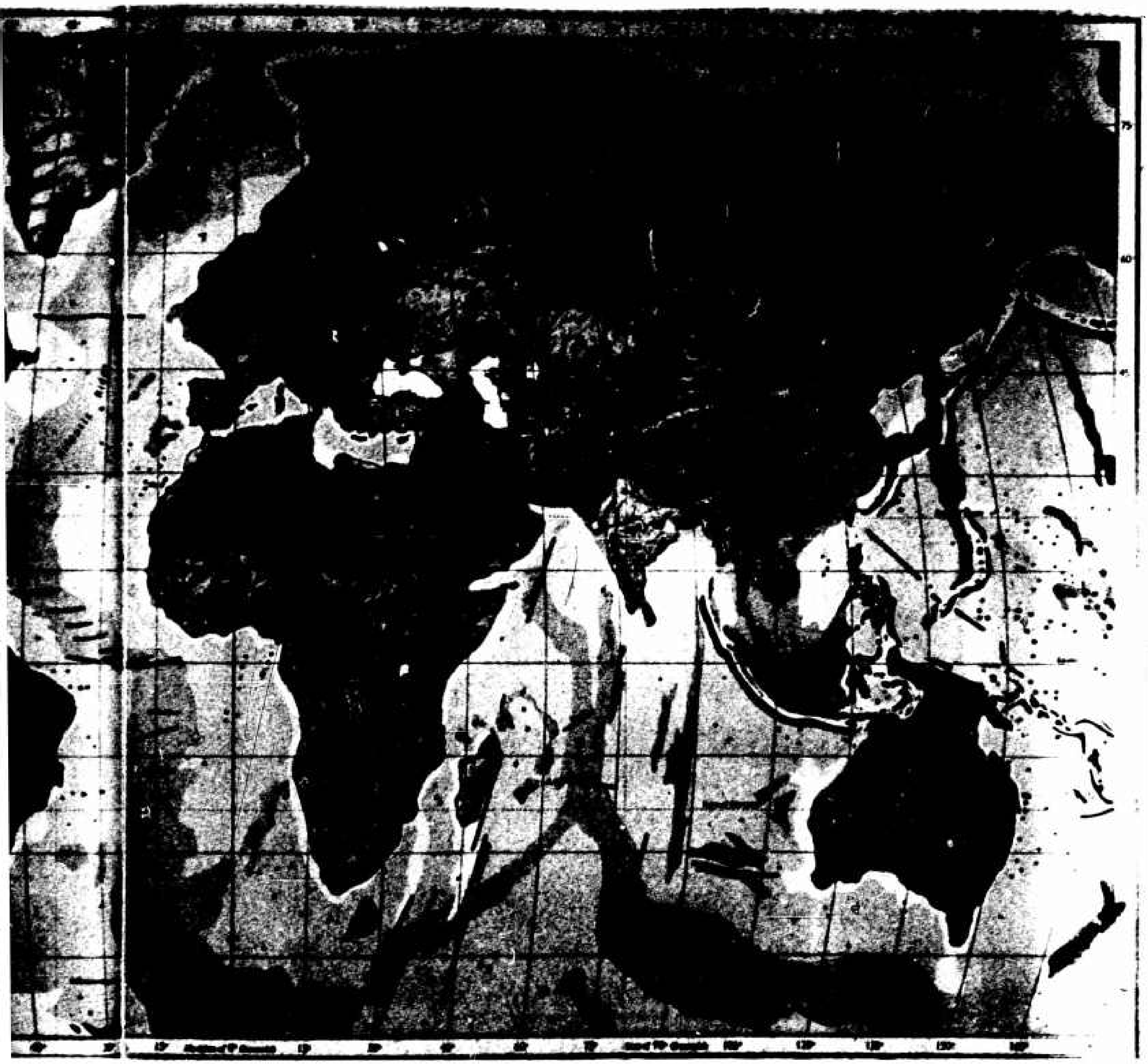
heating between summer and winter in both hemispheres. This results not only from an increase in the angle of incidence of the sun's radiation but also from a change in the length of the day. These seasonal changes in surface temperatures also lead to important changes in the strength and locations of land and sea pressure systems. Semipermanent high pressure systems over the oceans tend to move poleward somewhat in summer and retreat in winter. On the other hand, land surface temperatures are affected much more drastically between seasons and high pressures which may prevail over large land systems in the wintertime are often replaced by predominantly low pressure systems in the summer. Table 7-1 gives average hours of sunshine monthly for various latitudes in the Northern Hemisphere.

Table 7-1. Average hours sunrise to sunset.

Latitude (degrees)	Northern Hemisphere											
	J	F	M	A	M	J	J	A	S	O	N	D
0	12	12	12	12	12	12	12	12	12	12	12	12
20	11	11	12	12	13	13	13	12	12	12	11	11
30	10	11	12	12	13	14	14	13	12	12	11	10
40	9	10	12	13	14	15	15	14	12	12	10	9
50	8	10	12	14	16	16	16	15	13	11	9	8
60	7	9	12	14	17	19	18	16	13	10	8	6
70	0	7	11	16	22	24	24	18	13	8	4	0

The ratio of water-to-land surfaces on the earth is an important contributor to our climatic environment. The oceans occupy 71 percent of the earth's surface, the continents only 29 percent. It should also be noted that by far the most massive continental areas of the earth lie in the northern hemisphere (Reference 4). See Figure 7-2.

Figure 7-2. World physiography.



The large ocean areas of the world are the primary sources of atmospheric moisture which is subsequently transported in the general circulation of the air and deposited as precipitation in various seasonal and geographic patterns over the continents (References 5 and 6). Warm air can evaporate and retain much larger quantities as water vapor than can cold air. It, therefore, follows that the tropical and subtropical ocean areas supply significantly more moisture to the atr sphere than the waters of the polar regions. This consideration leads to a highly useful characterization of the atmosphere, the formation of air masses.

An air mass is a large body of air often a thousand or more miles in diameter which remains over a water or land surface long enough to acquire the temperature and moisture characteristics of the underlying surface. Since the oceans are the major supplier of moisture to the air, air masses which form over the oceans are primarily moist. The continents, on the other hand, having much less moisture to evaporate are the origins of dry air masses. Using these combinations of moisture and temperature descriptors, four major types of air mass of primary concern are described. They are:

- mT - Maritime Tropical, a warm moist air mass
- mP - Maritime Polar, a cool and moist to moderately moist air mass
- cT - Continental Tropical, a hot dry air mass
- cP - Continental Polar, a cold dry air mass.

These air masses are associated with pressure systems and eventually move, or parts of them break away and move often for thousands of miles. As they leave their regions of origin, air masses are modified either in temperature or moisture and change in pressure as they pass over other types of land and water surfaces.

A final determinant of forest and climatic types is the size and shape of a continental land mass and the configuration of the surface topography. Some of the more striking features are shown in Figure 7-2. Land surfaces offer much greater friction to the free movement of air over the surface than do water surfaces. In fact, every ridge and valley system has its own local climatology and frequently its own local vegetation associations. Space here, however, permits consideration of only some of the effects of the principal mountain ranges of the world.

Every mountain range is a definite barrier to free air flow. In the case of a cold dense air mass the mountain barrier may either divert its direction of motion or cause it to stagnate until it deepens enough to flow over the crest. When this occurs the cold dense air usually flows down the lee slope of the range warming as it descends and becoming drier in terms of its relative humidity. In the case of a warmer air mass, pressure gradients may be sufficient to cause the air to flow up and over the barrier where it then proceeds to flow leeward at the approximate elevation of the crest. It has been noted frequently that this type of flow results in a series of mountain waves to the lee of the mountain crest. If warm air forced over a mountain range happens to be moist, it is cooled in the lifting process and may reach condensation temperatures. In this situation clouds and often heavy precipitation are found on the windward slopes. This is one way that air masses are often drastically modified. On reaching the crest the air, having lost much of its moisture, may either flow on downwind aloft or descend downslope depending on the characteristics of the air mass on the lee side of the slope. In either situation mountain chains create dry rain shadows which drastically modify the leeward regional climate.

In addition to their effects on airflow and precipitation distribution, mountain systems often have different forest and climatic zones that are dependent upon altitude (Reference 7). This differentiation is caused by decreasing temperatures with increasing altitudes. The zonation is much more marked in the tropics than in the polar regions. In the tropical Andes of South America, for example, vegetation extends from near sea level with a number of distinctive vegetation type changes to an upper limit of 15,000 to 16,000 feet. In the northern mountains of western Canada and Alaska, on the other hand, not only are the vegetation types fewer, but they are also limited to a maximum altitude of only about 3,000 feet. Some of the topographic effects are elaborated in Chapter 8.

Other geophysical determinants of forest type include geologic formations, soil types and the retention or drainage of soil moisture. These factors are important in outlining different vegetation areas as delineated on maps. These factors are not treated here because once type boundaries are established, these geophysical differences must be evaluated in relation to fuel moisture content and flammability on a wholly local basis.

7.3 CLASSIFICATION OF FOREST FUEL TYPES

In Chapter 6 the need was indicated for grouping or classifying wildland vegetation types somewhat differently from the manner in which they have been grouped for blowdown purposes. The difference lies in the fact that the physical properties of a forest that determine its blowdown potentials are not, in themselves, indicative of forest flammability. Therefore, for fuel type classification purposes wildland vegetation has been grouped into fourteen broad forest types, each of which has climatically associated relationships which together define world-scale fire potentials (Reference 8). Purposely excluded from the following discussion is Type XV and areas in high, rugged mountain topography of little thermal consequence to operational activity.

FOREST FUEL TYPES

I. Tropical evergreen rain forest
II. Tropical semideciduous forest
III. Tropical savanna
IV. Tropical and desert scrub woodland
V. Coastal lowland
VI. Mid-latitude savanna
VII. Mediterranean scrub woodland
VIII. Mid-latitude coastal evergreen forest
IX. Mid-latitude broadleaf evergreen forest
X. Mid-latitude broadleaf deciduous forest
XI. Mid-latitude conifer forest
XII. Mid-latitude mixed wood forest
XIII. Boreal forest
XIV. Tundra
XV. Barren

Note that these types are listed in order, for the most part, from tropic to polar regions to facilitate somewhat their association with climatic differences. The last two types are confined to the Northern Hemisphere. The remainder are found on both sides of the equator.

From what has been said in this and the previous chapter, it is evident that a general forest-type label alone is, in most cases, a poor indicator of its fire potentials. No one of these types alone occupies any single broad geographical area. Significant differences occur within individual types under different climate and weather regimes (Reference 9) and, on the opposite end, fire may burn similarly in two different types under different or even the same weather systems. Another difficulty with this form of generalization is that there is too frequently a blending of one type into another, often with a broad transitional zone in between that is not particularly indicative of one or the other (Reference 10). In these cases the determination of type boundaries is often a matter of individual judgement. For intelligent interpretation of forest types in terms of fuel types for operational purposes, it is essential to describe an area of concern in much more detail.

A tree forest usually represents the most complex fuel type in which ignitibility and fire spread potentials are to be judged. To describe it reasonably, the following items are the minimum to be noted (Reference 11).

1. Tree Species or Species Association. Species gives an important clue to tree form or branching habit, the density of foliage within individual tree crowns, relative flammability of the living foliage, and the nature and relative flammability of accumulated litter on the forest floor.

2. Average Tree Height. This is an important factor in the geometry defining the size of an opening in the forest required for some point on the forest floor to be visible to the fireball at various slant angles. Together with other factors listed below, it helps to determine the drying regime beneath the canopy and the windspeed that can be expected within the forest.

3. Canopy Length. This element, representing the proportion of total tree height occupied by tree crowns, is an important factor determining forest crowning potential and is also a factor in determining surface drying regimes and internal forest windspeeds.

4. Canopy Density. This element refers to the vertical projection of all canopy cross sections on the ground surface. Canopy density, in association with the elements above, helps to define forest ignitability and burning characteristics. It is further modified, however, by item 5.

5. Horizontal Continuity. This element describes the characteristics of horizontal canopy density by defining such things as crown areas occurring at random over the area considered or according to the frequencies and sizes of significant openings in the canopy.

6. Dead Fuel Descriptors. This element should be divided into three parts: first, an appraisal of the frequency and distribution of tinder fuels, ignitable by the thermal pulse; second, a description of the kinds and amounts of leaf and needle litter on the ground responsible for the principal fire spread together with branches, limbs, and logs which furthermore add to the intensity of surface fires; the third part is related to dead fuels attached to tree trunks and distributed in tree crowns, dead trees or snags, and such things as draped lichens which may facilitate the spread of surface fires into the crowns.

7. Associated Vegetation. This refers primarily to understory vegetation such as reproduction, shrub, grass, and other plants which may either add to or detract from the surface fire spread and intensity according to their relative flammabilities.

8. Vertical Continuity. This term refers to the continuous availability of flammable fuels above flame height of surface fires capable of extending surface fires into the crowns and the development of crown fires.

9. Sources of Firebrands for Spot Fires. These may be sparse or plentiful in almost any forest type. They include a wide variety of substances among which the more common are dead and rotten wood aloft, cones of conifers, the scaly bark of some species among which eucalyptus (Reference 12) and paper birch are notorious, and both living and dead leaves of many species.

The mathematical integration of all these complex factors for estimating probable fire phenomena are still beyond the state-of-the-art. For the same reason it is also only possible to specify their individual characteristics and combinations, for the most part, in very general qualitative terms for which no specific guidelines have been established. What is more, quantitative estimates of most of these on an operational scale are either impractical or impossible to obtain, even if specific requirements could be provided.

In the absence of intensive ground reconnaissance, reliance for information on forest fuel parameters must be placed on air photograph interpretation, supplemented where possible by aerial reconnaissance. Even with ground access aerial photograph interpretation is a most valuable beginning point for delineating local types and subtypes (Reference 13). From them it is also usually possible to estimate tree heights, crown lengths, and crown densities and continuity with useful accuracy. More difficult and often usually equally important is a reasonable description of the understory vegetation (Reference 14). For this purpose color photography, for example, using Ektachrome Type 2448 at a scale of 1 to 8,000 may prove most useful.

Care must be taken in aerial interpretations not to be misled by looking at conditions along the edges of roads and clearings where undergrowth is almost always the most dense. Emphasis should be on tryir , to look through small gaps in the tree crowns and in the smaller openings. Litter and other dead fuel characteristics may have to be estimated by a ground reconnaissance in forests of similar composition in adjacent areas. If possible observations from low-flying low-speed helicopters may often provide useful information with respect to both the understory vegetation and the dead fuel situation.

7.4 CLASSIFICATION OF CLIMATE TYPES

In the past climates have been classified by numerous authors to serve diverse purposes. None of these classifications by itself, however, is completely descriptive of climate relating to the fire-proneness of the world's vegetation types. For a worldwide climatic classification more or less compatible in scale and scope with the selected world forest types, a slight modification of the Koppen System (Table 7-2) serves as a useful guide (Reference 15).

Various climatic classification systems are based, in part, on average daily and average monthly temperatures. The more sophisticated of these computes average daily temperature by integrating the actual temperature over a 24-hour period. The average monthly temperature is then taken as the arithmetic average of these daily temperatures. A less sophisticated method, but one which produces equally useful average monthly temperature data, computes average daily temperature as the arithmetic average of the maximum and minimum temperature for the day. Average monthly temperatures are then computed as above. Because of its simplicity this latter method of averaging maximum and minimum temperatures to derive daily and monthly averages will be used in our case. The modified Koppen classification which follows may be interpreted in these terms.

Table 7-2. Modified Koppen classification of regional climate types.

Type	Subtype
A - Tropical forest climates; coolest month above 64.5° F	a - Warmest month above 71.5° F b - Warmest month below 71.5° F c - Less than four months over 50° F
B - Dry climates BS - Steppe or semiarid climate BW - Desert or arid climate	*d - Same as "D" but coldest month below -25° F f - Constantly moist, rainfall all through the year *h - Hot and dry; all months above 32° F
*C - Mesothermal forest climates; coldest month above 32° F, but below 64.5° F; warmest month above 50° F	*k - Cold and dry; at least one month below 32° F m - Monsoon rain; short dry season but rainfall sufficient to support rain forest
*D - Microthermal snow-forest climates; coldest month below 32° F, warmest month above 50° F	n - Frequent fog n^1 - Infrequent fog, but high humidity and low rainfall s - Dry season in summer
E - Polar climates ET - Tundra climate; warmest month below 50° F, but above 32° F EF - Perpetual frost; all months below 32° F	w - Dry season in winter *x - Dry season in spring or fall
*F - Mountain-valley climates FM - Massive systems FS - Secondary systems	
*Modification of Koppen	

The original Koppen classification designed to describe climates in relation to vegetational kinds and activity has been modified slightly to make it most adaptable to the description of flammability climatic factors. This, for example, in association with fuel type provides a reasonable basis for estimating expected accumulations of surface litter and dead wood in the type (References 16, 17 and 18). These are both important flammability parameters.

Most forest types of the world are more or less fireproof during part of the year and are susceptible to ignition and burning in varying degrees during so-called "fire seasons." These may vary in different regions from perhaps two or three months to virtually year round in others. The operational objective is to identify those periods when fires are likely to occur and to characterize their expected relative severities. It is apparent that the above climatic classification falls short of the requirements for this determination. More specific local climatological data is therefore needed for operational applications. The information indicated in Table 7-3 represents the approximate minimum requirement for this purpose.

Where available climatic records indicate days of precipitation of less than 0.1 inches, the following conversion (Figure 7-3) may be used to compute the desired entry in the table.

Table 7-3. Required climatic data.

Station______ Lat.______ Long.______ Elev.______

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Snow Covered													
Av. Precip.													
Rainy Days[a]													
Av. Mo. Temp.													
Av. Max. Temp.													
Av. P.M. RH[b]													
Length of day[c]													

[a] Days with 0.1 inch or more
[b] As of 1300 hr or later
[c] From Table 7-1

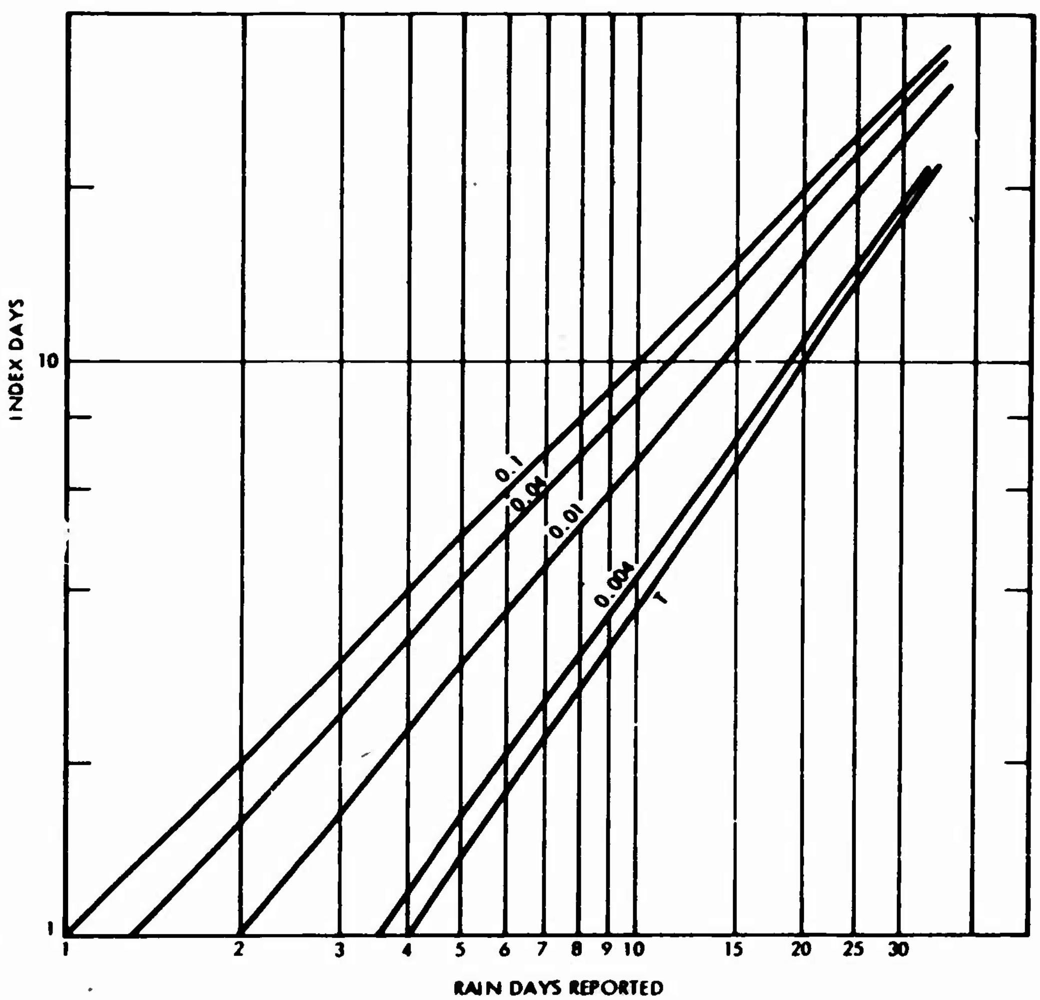


Figure 7-3. Factors for converting recorded rainy days per month to different bases. (From statistical analysis of rainfall data by Craig C. Chandler and George W. Fernival, Washington D.C., 1965.)

As will be indicated in the next section, each of these records must be interpreted according to the particular fuel type to which it applies. In using Table 7-3 it will soon be obvious that it is unnecessary to complete all entries for all months except those in which fires may occur. Precipitation and average monthly temperature are the main exceptions. Total annual precipitation is an important entry.

Perhaps even more important in interpreting climatic data is the frequency and extent of annual deviations from average annual values of the various weather parameters. Yearly records are required for this purpose, but the extra effort in analysis may pay big dividends in estimating probabilities for any particular time period.

7.5 CHARACTERIZATION OF FOREST AND CLIMATE TYPES

The characterization of forest and climate types on a world scale in most cases can indicate only a few representative examples of the kinds of situations that may be found in any area of particular interest. The principal reasons for this are that forest regions on a world scale indicate only the boundaries of areas in which a typical forest may occur, rather than its specific area of occurrence, and that climatic regions are established in the same way. One notable feature is that areas under cultivation are ignored, a factor which makes it impossible to ascertain forest-type continuity or whether or not such types even exist. China is a good example. Most type classifiers indicate much of China as forested, presumably largely through association with climatic regions, whereas only 7 percent of China is in tree forests. The largest remaining natural forests are in the less accessible areas of the northeast, inner Mongolia, and southwest China. There has been some reforestation, but these areas are small. Similar situations exist in most inhabited parts of the world, though generally on a lesser scale. This would justify consideration of an addition of a Type XVI, Agricultural, where data permits.

With the above reservations in mind, we can proceed to describe typical characteristics to be found in the various forest fuel type regions, some of their climatic characteristics and their susceptibilities to fire (References 8, 19, 20, 21, 22, 23, and 24).

7.5.1 Forest Fuel Type Descriptions

TROPICAL EVERGREEN RAIN FOREST. This type consists of hundreds of species of broadleaf evergreen trees with the upper canopies often reaching 120 to 150 feet in height or more commonly, with one or two understory canopies and profusely endowed with rank-growing vines or lianas, there is no dormant season. The type occurs in tropical regions of all the continents and principal island systems wherever the climate may be classified as Af, that is with the coldest month above 64.5 degrees F., constantly moist with rainfall occurring throughout the year. Average monthly temperatures usually vary only 4 to 8 degrees F. throughout the year and are usually some 10 to 15 degrees warmer than the specified lower limit. Annual precipitation is usually in excess of 100 inches per year, but may be less if the forest is under the more or less continuous influence of mT, warm moist marine air. The type is confined to lowlands, mostly below 3,000 feet above sea level.

The combination of continuously high temperature and moisture results in extremely rapid decomposition of dead forest materials; consequently, there is no deadwood in the forest and even the surface litter decomposes so rapidly that it consists of only one or two leaf thicknesses, a quantity insufficient to carry spreading fire even if dry enough to burn. Since the living foliage is nonflammable, the tropical evergreen rain forest must be considered as a nonfire type. Even though the rain forest is susceptible to nuclear blowdown, the resulting debris will not burn until after several weeks of desiccation and then only during infrequent favorable burning conditions.

Openings in the rain forest are often occupied by bamboo thickets. Bamboo, a tropical savanna type, is relatively nonflammable, even when dead, probably because of a high mineral ash content. Bamboo is, therefore, also a nonfire type.

TROPICAL SEMIDECIDUOUS FOREST. The semi-deciduous forest formation is distinguished from the evergreen rain forest by a number of qualities. It commonly consists of two definite levels — an upper level of moderately tall, slender broadcrowned trees and a lower layer of chiefly evergreen trees and shrubs in thick-growing profusion. Climbing vines and woody stems are also prolific. The trees in the upper layer commonly range from 65 to 85 feet in height with stems of only moderate size that begin to branch low down on the stems expanding into umbrella-shaped crowns over head. This results in a closed forest except where the type approaches its drier boundaries where the forest may become more open.

Like the tropical evergreen rain forest, this type occurs in regions of high nearly constant year-round temperatures, but usually with somewhat less annual precipitation which is punctuated by a period of one to 5 months is which the precipitation is 2 inches a month or less, and often not more than 1 inch. The season in which the dry period occurs varies from one geographical region to another. The number of tree species in this type is still numerous, but much less so than in the rain forest. Depending upon the geographical region, from 25 to 65 percent of the upper level trees are deciduous, losing their foliage entirely during the less rainy season.

This seasonal opening-up of the upper canopy contributes much to the lushness of the lower evergreen species. Generally these latter have smaller leaves than are found in the rain forest and are characteristic of vegetation that must survive periodic water deficits.

None of the living foliage of the species in either the upper or lower vegetation level is flammable and the warm, humid climate leads to the rapid decomposition of both litter and deadwood. Consequently, in this forest type there is little to burn and the type is not recognized as a fire type. When subjected to blowdown, on the other hand, the resultant debris will only require a short time to become flammable during the dry season.

TROPICAL SAVANNA. The tropical savanna formation is dominated by extensive grassland often incorporating a good percentage of sedges in which scattered trees and shrubs are common. It also includes the bamboo thickets mentioned in connection with the tropical evergreen rain forest. The most impressive aspect of the grass savannas is the openness of the landscape. There is a clear view of the horizon interrupted at random intervals by clumps of trees and more frequently by individual trees and shrubs. The type is often penetrated by sinuous lines of dense forest and undergrowth in the bottoms of rivers and tributary streams that occasionally penetrate these areas. These generally narrow riparian forests frequently resemble the luxuriance of tropical evergreen forests in number of species and in outward aspect of height and stratification.

The character and floristic composition of the tree and shrub vegetation of the tropical savanna regions vary too widely to permit a generalized type of description. In many areas the trees are deciduous and are often low broadcrowned forms ranging in height from 15 to 30 feet. They are frequently twisted and stunted in appearance. In other regions they are evergreen and relatively tall and straight. These include the palms and locally, in parts of Central America, pines. Lianas and epiphytes are scarce. Grasses of the tropical savanna are also quite variable though usually luxuriantly dense. They vary from one region to another from about 1 foot to very tall forms 12 to 15 feet high.

The tropical savanna occurs in a definitely tropical region with all months averaging over 64.5 degrees Fahrenheit. It rarely occurs wherever there are extremes of either heat or cold. Moisture-wise the tropical savanna occurs in regions that vary considerably in annual average precipitation, but generally fall somewhere between the monsoon climate and the hot dry climate. There is a definite dry season, usually not longer than about 5 months. Precipitation during these dry season months may often be one-half inch or less per month.

The tropical savanna type, excluding bamboos, is definitely a fire type. The grasses generally support fast-moving fire soon after the beginning of the dry season when the grasses cure and dry with fire intensities varying primarily according to the height of the grass. The overstory vegetation of trees and shrubs has little influence on surface fires supported by the grass. Forest blowdown is generally of little significance in this type.

In certain tropic regions of the world there are extensive grasslands at high mountain elevations which, because of the altitude, are more typical of mid-latitude savannas and are not included in the tropical savanna type.

TROPICAL AND DESERT SCRUB WOODLAND. The tropical scrub woodland formation is somewhat similar to the tropical savanna in its general appearance of openness. Woody plants are dominant. They are usually smaller than those in the tropical savanna and in some regions are commonly deciduous. However, there is much variety and in many areas the trees and shrubs are evergreen. The number of plant species is quite limited and broadcrowned trees and shrubs with short distorted trunks are common. Long, thin-stemmed lianas are plentiful but the vegetation is usually poor in epiphytes. Where low-growing scrub forms are abundant the ground is often bare beneath. In many areas, however, grasses play an important role in the composition of the ground cover beneath the dominant woody overstory.

Tropical scrub woodland replaces the tropical savanna where temperatures range within higher limits and where strong daily and seasonal temperature fluctuations prevail. Annual precipitation is normally less than in the savanna and the dry season often persists for as long as 8 months. This is more typical of a continental climate. Mid-latitude desert scrub woodland is included in this group because of similarities in both vegetation forms and climatic regimes.

Climatically the tropical scrub woodland would be classified as Ah (Table 7-2) and the desert scrub would be classified as BWh. In both cases the dry season of the year will varv according to the geographic region.

Scrub woodlands accumulate neither appreciable quantities of deadwood or litter. Their flammabilities therefore depend primarily on the presence of grass in sufficient quantity to support a surface fire. Where grass and evergreen woody vegetation occur together, flammable evergreen foliage may add appreciably to the fire intensity. Wherever fuels permit, the fire season begins shortly after the onset of the first dry months. Blowdown is not expected to be a significant factor in these scrub woodland types.

COASTAL LOWLAND. Many tropical and subtropical regions are bounded on their seaward edges by swampy lowlands. These support various types of vegetation that are not dependent on climatic influences alone. In many of these reeds, rushes, and marsh grasses are often the prevalent vegetation forms. These lowlands may be submerged year round except in drought years, submerged part of the year and dried out during a dry season, or in the case of many of the major river delta systems, they may be submerged only during flood stages. Some of these coastal lowlands are invaded by salt water from the sea in which case they are often covered with dense vegetation in which one or more types of mangrove trees and shrubs are often dominant.

No attempt is made here to characterize the climates associated with these lowland types because of the considerable variability among them. Wherever dry seasons occur, however, the grasses, rushes, and reeds become flammable and may burn with considerable rapidity even over exposed water. The tree types, on the other hand, rarely pose a significant fire threat even with forest blowdown.

MID-LATITUDE SAVANNA. The mid-latitude savanna is empirically defined here, as it is for the tropical savanna, as any area with a 50-percent or more ground cover of grass or grass-like plants in which tree or shrub crown density, where present, is usually less than 25 percent. Included in generalized world maps are many agricultural areas bearing seasonally flammable crops including vast areas of cereal grains. In natural situations it is often difficult to define exact boundaries between woodland savanna and forest types as they blend together, frequently with fingers of one extending for considerable distances into the other.

Throughout the world savannas are known locally by many names. Among the more prominent of these are: savanna, savanna woodland, woodland, prairie, steppe, pampas, monte, veld, reeds, and marsh grasses. For convenience we add paramos, meadowland grasses of the Andes, and other high altitude tropical regions. In these cases the effect of altitude on climate and vegetation is similar to the mid-latitude or even polar regions.

The grasses are among the world's most varied and most widely distributed flowering plants. They are found in successful adjustment to habitats which are too wet or too dry for trees. The principal mid-latitude savanna climates, however, are generally intolerable for persistent forest growth and yet moist enough to support a complete cover of grass. In this sense they are regions of transition between well watered forest and water deficient desert. With the exception of the high altitude grassland, the savanna is most common on terrain that is level to rolling or hilly, and ranging in altitude from sea level to about 7,000 feet. Their latitudinal range north of the equator is from about 30 to 55 degrees and south of the equator from about 23 to about 50 degrees. The major savanna climates of the middle latitudes are found in five principal areas: the central interior of North America, the central interior of Eurasia, southern South America, southern Africa, and southeastern Australia. Although the savanna is found in scores of lesser areas elsewhere within the mid-latitudes, these five areas are the largest and serve as the prototypes of the savanna climate on each continental land mass.

The climates of these principal savanna regions are predominantly continental. They exhibit both diurnal and seasonal temperature extremes, particularly at the higher latitudes. Precipitation commonly is highest during the summer months falling principally in the form of short but intense convective storms. These are frequently interspersed with days of clear weather, high temperatures, low humidities, and often strong winds. The resulting evapotranspiration may thus offset, to a considerable degree, the otherwise effective precipitation amounts. In the more temperate savanna regions the annual precipitation cycle may be reversed with the greater amounts falling in the winter months.

In bog and marshland areas the vegetation which dies each year is deposited beneath the water surface and is eventually incorporated into the organic soil which supports the vegetation. In the dry land areas, on the other hand, much of the vegetation is harvested by wild or domestic animals or by man and natural decomposition takes care of the rest. One striking feature of these dryland types is that the annual vegetation growth is very sensitive to deviations from the normal in both seasonal distribution and amounts of precipitation. Droughts with minimal vegetation growth are common.

The fire season in any of the savanna types occurs whenever the vegetation is matured, except when covered with snow, and ends with the dominance of new growth soon after the beginning of the rainy season. Blowdown is of little significance in the savanna with two exceptions, one is in the tall grass savanna where height of the vegetation may serve as a horizontal shield for ground personnel and the other is in the savanna woodland where single trees or groups of trees serving the same purpose may be blown down eliminating the protective cover.

MEDITERRANEAN SCRUB WOODLAND. The Mediterranean scrub woodland type is unique among the mid-latitude forests of the world. Its climate is distinguished chiefly by its very warm dry summers, mild wet winters and a large amount of clear sunny weather throughout the year. It can be considered, in general, as a transitional type between the humid forests on its northern margins and the treeless savannas and deserts toward the equator. This climate can generally be classified as Cas (see Table 7-2).

This type is not extensive, mostly within 100 miles of the sea, and normally at altitudes less than 4,000 feet. It is furthermore uniquely confined to west coastal situations on the world's major land masses.

In the northern hemisphere it extends from about 30 degrees to about 45 degrees and south of the equator, from 30 degrees to 35 degrees. The type appears most extensively on the shores of the Mediterranean Sea from which it gets its name and in other smaller, widely separated areas: California, Chile, and southwestern Africa.

The most widely characteristic vegetation of this Mediterranean type is a shrub thicket of woody plants best known as Maquis and its less dense form Garrigue and Chaparral in the United States.

The vegetation is typically broadleafed evergreen, the foliage consisting predominantly of small leaves and commonly provided with such drought-protective devices as hard, shiny or waxy surfaces, hairs, thorns, and relatively few stomata. The living foliage is usually high in crude fat content. Tree forms of vegetation are often found within the type consisting typically of broadleaf and coniferous evergreens of low to moderate height and with broad rounded crowns often supported on short heavy trunks, having rather thick bark, and fed by extensive root systems. Trees are not always present, but when they are they appear in scattered clumps or individually separated by wide areas of brushland of varying density and occasionally by savanna.

In general, the Mediterranean scrub type accumulates only minimal quantities of surface litter but invariably sufficient to carry fire into the highly flammable foliage and associated attached dead branches and twigs in the shrub crowns. The type is generally considered a fire-prone type at any time of the year when weather conditions are favorable to fire except perhaps for a period of a few weeks of lush new growth in good growing years. Also in some regions this type is often subjected to strong desiccating winds, causing fire to spread very rapidly and with great intensity. The type provides good cover for ground troops but may prove to be a death trap in the event of fire. The type is generally trafficable to tracked vehicles which can smash down the brush, but here again fire may be able to travel much faster than the vehicles themselves.

Little is known about the susceptibility of Mediterranean scrub to blowdown, but the general makeup of the type suggests that the effects of blowdown will not be serious much beyond relatively high overpressure distances.

Regarded by some as an analogous growth, the Mallee associations of Australia are a clumpy tree form, generally 20 to 40 feet high and are only fire prone on an average of once in 15 years, due to the fact that there is generally insufficient fuel between the tree clumps to carry a continuous fire. It is only in occasional years, following very much above average winter and spring ~~rainfall, that grass~~ will grow in the interclump spaces and provide sufficient fuel continuity to carry high intensity fires. Thus, in most years this type would provide good cover for ground troops and be quite safe.

The northern extension of this type of country which fringes the semi-desert regions of the continent is the Brigalow scrub, dominated by Acacia species as distinct from Mallee which are dominated by Eucalpt species. As with the Mallee, fire will not normally travel through this type, except in very occasional years when there has been exceptional winter or spring rainfall (a probability estimated at once in 25 years).

The association which probably most closely resembles the Maquis and Chaparral formations in southern Australia is the saltbush/blue-bush formations which are a true shrub association, but which fortunately is composed of fire retardant species such as atriplex. Fire rarely travels through this association.

MID-LATITUDE COASTAL EVERGREEN FOREST. The mid-latitude coastal evergreen forest, like the preceding Mediterranean scrub woodland type, has only a limited worldwide distribution. Like that type as well, the evergreen forest is restricted to relatively narrow coastal belts mostly on the western shores of several of the continents. The coastal evergreen forest, on the other hand, is strongly dominated by a maritime climate. Annual precipitation may range from about 60 inches to over 200 inches per year. Another difference is that the coastal evergreen forest does not have the same annual climatic regime as the Mediterranean type.

The largest area of coastal evergreen forest occurs on the west coast of North America, extending from Kodiak Island in Alaska to San Francisco. This wide latitudinal range results in somewhat different climatic regimes from north to south. The vegetation in general may be characterized as lush. The northern forest is completely coniferous with trees increasing in height and volume to about the mid-portion of the region and finally terminating in the south as a mixed coniferous and broadleaf evergreen forest.

The type is found in southwest South America, south of about 40 degrees latitude and extending to the Straits of Magellan. This is a lush forest region consisting of some conifers and predominantly evergreen broadleaf trees. Temperatures in this region are moderate with the range of temperature between the warmest and coldest months averaging less than 10 degrees at most locations. Moisture is also monotonously plentiful year round. When it is not actually raining, the relative humidity averages between 80 and 95 percent from one end of the year to the other and the mean cloud cover for the year averages about 80 percent. This varies less than 10 percent from one season to another.

A third region of coastal evergreen forest is found along narrow strips of the western European coastline. It extends in relatively narrow segmented strips from southern France to the Netherlands on the mainland and occurs on the west coast of each of the British Isles. This is a region of temperate marine climate closely similar to that of the North American coastal evergreen forest. Annual precipitation ranges from about 60 to nearly 200 inches per year with somewhat more than half falling in the period from October through April. However, coastal fogs are frequent throughout the year accounting for the presence of a luxuriant growth of broadleaf evergreens along with conifers.

The fourth general region of occurrence of coastal evergreen forest is found on the west coast of the south island of New Zealand and on the west coast of Tasmania. Both of these areas are subjected to temperate marine air with annual temperatures rarely varying more than 10 degrees from the warmest to the coldest month. Annual precipitation is mostly in excess of 60 inches a year and is distributed rather uniformly through the year as a result of frequent east-moving cyclonic storms. These are frequently interspersed with clear sunshiny days often with considerable wind. The forest in both cases is luxuriant broadleaf evergreen. This type occurs locally in the southeast Australian mainland, but not on the continent of Africa.

Coastal evergreen forests in general are not fire prone. There are local exceptions as in the south central portion of the North American segment during drought years. Fog is frequent in many areas even during dry periods. There are often heavy accumulations of litter and logs on the forest floor. Because of lush growth and often exceptionally tall tree heights, blowdown may often create severe damage, but with the exception noted above will not significantly affect fire potentials.

MID-LATITUDE BROADLEAF EVERGREEN FOREST. The most noted broadleaf evergreen forests outside of the rain forests are the eucalyptus forests of Australia and Tasmania. Eucalyptus contains many species spread over various parts of the continent. Each is adapted to its particular climatic and edaphic regime. Southeastern Australia, under favorable maritime climatic influence, supports a lush towering eucalyptus forest including the tallest trees in the world. The various species of eucalyptus are the dominant trees of Australia. Many of them, however, occur as open woodlands classed as savanna and range on down to the Mediterranean type mallee, consequently the mapped area of eucalyptus as a forest is limited.

Other evergreen broadleaf trees such as live oak, magnolia, and other species occur in scattered localities in limited portions of east Asia and other parts of the world. In general, however, each locality is too small to be delineated on the world-scale map so it is included in other types. Similarly, scrub evergreen trees and shrubs are found scattered over all the continents, usually occupying sites and climatic regimes less favorable for full forest development but more favorable than that supporting Mediterranean scrub woodland types. In these latter, in particular, annual temperature variations are often more dominant features of the climate than is the moisture regime. These scrub types are often found in mixture with either conifer, broadleaf, or mixed wood types and are included for general classification purposes within them.

There must be some distinction made between the west coast of New Zealand and the west coast of Tasmania. In the case of New Zealand, the species are generally non-flammable and could certainly be classified as not being fire-prone. The temperate rainforest on the west coast of Tasmania however, contains eucalypt species mixed with nothofagus and is extremely fire prone at a frequency of perhaps once every 25 years when a drought period occurs. They carry extremely heavy accumulations of fuel, are very difficult to access, and blow down would create severe damage.

The climates which support mid-latitude broadleaf evergreen forests, although quite variable, are not particularly conducive to the rapid decay of litter and deadwood, hence these materials may accumulate on the ground in considerable quantities. The living foliage of these evergreen trees is also generally flammable, thus making all of them susceptible to crown fires during dry weather.

The eucalypt forests are particularly noted for the ready formation of crown fires both because of the high volatile oil content of their foliage and the fact that over half the ducalypt species are rough barked, which provides a fuel continuity between surface and aerial fuel. The gum bark eucalypts shed their outer bark annually in long rolled strips and this bark provides the material for spot fires which may light up at very long distances in advance of a fire front. Under extreme meteorological conditions spotting distances of 15 to 18 miles have been recorded on numerous occasions.

Blowdown debris from all of these forests will burn with high intensity during favorable fire weather.

MID-LATITUDE BROADLEAF DECIDUOUS FOREST. This deciduous forest consists of about 100 dominant species if some 40 or 50 closely related deciduous oaks are included as one species. The type occupies a broad latitudinal zone, mostly in the northern hemisphere, from about 30 degrees to 50 degree in North America and from about 35 degrees to 60 degrees in Eurasia primarily on plains, river bottoms, and rolling topography. The broadleaf deciduous forest in general occupies a transitional zone between the predominantly coniferous boreal forests of the north and those at higher altitudes and the more arid savanna or desert regions of the South. It is a common component of the woodland savanna on both continents. It occurs less abundantly in the southern hemisphere

Longitudinally the type is most common in eastern North America and extends with few breaks from western France to Japan in Eurasia. Thus while the type is predominantly influenced by the continental land masses, it also occurs in regions strongly influenced by moist marine air. In most regions, however, with annual precipitation varying from about 21 inches to more than 100 inches, the type occurs where the maximum yearly precipitation occurs in summer when the trees are in leaf so that it often has a spring or fall dry season, or both, when the trees are bare and thus often causing a split fire season.

Occupying such a broad latitudinal range, annual and seasonal temperatures vary widely. Snow and below freezing temperatures are common throughout the northern portions in winter and only occasional winter frost occurs in the southern regions.

Undisturbed broadleaf deciduous forest commonly grow in stands with a closed canopy, thus providing shade, protection from wind, and high humidity near the surface during the leaf-bearing portion of the year. These are changed drastically when the leaves fall. Draped lichens are usually absent.

This type occurs in a range from a warm, humid climate to that of a colder less moist situation. Over this range there is considerable difference in the rate of accumulation of leaf litter and deadwood. In the southern extremes rapid decomposition tends to limit accumulations to minimum levels and in the northern portions litter accumulation may be several inches deep and dead trees and surface deadwood are common.

Broadleaf deciduous forests, with the exception of some scrub types in drought years, are not susceptible to crown fires. During dry periods slow burning surface fires may occur when the trees are in leaf and burn much more rapidly and more intensely when bare.

Due to branching habit many of the deciduous hardwoods will break up under blast loading from nuclear detonations or be uprooted. In either case the volume of stem and large branch wood falling as debris will be much greater than in equivalent stands of conifers. Days to weeks of drying are required for new fallen deciduous broadleaf debris to add fuel in support of fire.

MID-LATITUDE CONIFER FOREST. Mid-latitude conifer forests consisting of cone-bearing trees contain several hundred species distributed in both the northern and southern hemispheres. They are much more numerous and diverse in the north where they more frequently occur in pure stands of single species or in stands of mixed conifers to the exclusion of more than 25 percent of the area occupied by intermixed broadleaf trees.

In western North America conifers extend from about 10 degrees north latitude in Central America to about 60 degrees north latitude in the Canadian Rockies. On the eastern side of the continent they extend from about 20 degrees in the Caribbean to the Great Lakes and New England where they merge with the predominantly coniferous boreal forest to the north. They do not occur in the Central Great Plains Region.

In South America coniferous forests occur primarily along the Ande chain from Colombia and Ecuador to the southern tip of the cor They also occur in Brazil, south of the tropical rain fo nes do not occur in South America although several other ge some exclusive to that continent, are represented.

In Eurasia mid-latitude coniferous forests extend intermittently from the British Isles to Japan. In Europe they extend from about 25 degrees north latitude to slightly more than 60 degrees in Finland and the Soviet Union. In Asia they reach from about 15 degrees north latitude in the southeast, north to 45 to 50 degrees in Siberia where they merge with the boreal forest.

Conifers are restricted in Africa primarily to limited areas at the higher altitudes and in Australia to a few favorable growing sites.

This tremendous range of the conifers exposes this type to an equally broad range of climates, each pertinent to its own region. In virtually all regions, however, the conifer forests accumulate sufficient surface litter to carry fire. There is greater accumulation in the higher latitudes than in the lower, and since living conifer foliage is itself generally considered flammable, conifer forests are particularly fire-prone.

The branching habit of conifers is such that central main stems may break in response to a nuclear blast wave often near bases of the crowns or below, or the trees may be uprooted. More radially-oriented stems on the ground following blast are expected for conifers than for broadleaf forests. Blowdown debris does not require significant drying to add materially to surface fuels.

Only one conifer of wide distribution, larch, is deciduous. In North America this tree grows mostly in mixture with other conifers, but in northern Siberia it occurs in extensive pure stands. In the leafless condition blast damage would be minimal though surface fires would be numerous.

MID-LATITUDE MIXEDWOOD FOREST. The term mixedwood forest is used in this context to describe a forest fuel type consisting of a mixture of deciduous broadleaf and conifer trees the crowns of which must each equal or exceed 25 percent of the land area. This terminology is used to distinguish this fuel type from the classical mixed-forest type which consists of two or more dominant tree species.

The mixedwood forest as used here, on the other hand, only distinguishes between the broadleaf and conifer tree forms without regard for the number of species which may be present in either. In our worldwide consideration of the mixedwood forest, it is necessary to note three typical formations in which the type occurs. In the first formation broadleaf and conifer trees occur in random mixture without any particular pattern. In the second, characteristic of managed forests, the type occurs as separated tracts of deciduous forests that may alternate with coniferous forests. The third, occurring in mountainous areas with marked altitudinal zones frequently exhibit broadleaf deciduous trees on the lower slopes and valley bottoms with coniferous forests occupying the upper, cooler, better drained though frequently better watered higher elevations. For operational purposes these three subformations should be separately delineated and designated as mid-latitude broadleaf deciduous forest, mid-latitude conifer forest, or in the first case as mid-latitude mixedwood forest. In the present worldwide treatment these must be grouped because specific type boundaries cannot be delineated with useful accuracy.

The mid-latitude mixedwood forests occupy about the same worldwide geographic areas as the mid-latitude broadleaf, deciduous forests. Thus they are dominated by continental climates from high to low latitudes but with numerous areas under strong maritime influences. Therefore it is impossible to classify the climatic regimes for all areas in which the type occurs.

Because mid-latitude broadleaf deciduous forests and mid-latitude conifer forests have already been discussed, this section will be confined to consideration of the subtype in which both forms occur in varying proportions in intimate mixture.

In this mixedwood type surface fires will spread comparatively slowly when the deciduous trees are in leaf. Single conifer or small groups of conifer trees may crown out if the tree crowns are low enough to be ignited by the surface fire. In this process adjacent broadleaf foliage may be scorched and killed but will not support a continuing crown fire. The overall intensity of the fire and its possible damaging effects will increase in proportion to the conifer trees that crown. If the stand is predominantly coniferous, 60 to 70 percent for example, crowning may be continuous, more or less, leaving killed but unburned broadleaf tree crowns. When the deciduous trees are not in leaf, surface fire spread rates and intensities will increase in proportion to the fraction of the stand occupied by broadleaf species and crowning potential and intensity in the conifers will increase correspondingly.

In this type either flammable or nonflammable undergrowth may be present that will affect the overall fire behavior. In many instances it may be absent entirely. Litter accumulation will depend upon the species and their relative proportions in the stand, but it will generally increase poleward from the subtropical regions.

Blowdown in the mid-latitude mixedwood forest will be directly related to the stand composition. In each case broadleaf deciduous debris will dampen surface fire behavior while coniferous debris will enhance it. The ultimate result will depend upon the relative quantities of the species involved.

BOREAL FOREST. The boreal forest is the most northern circumpolar region of closed forest tree growth. It is confined to the Northern Hemisphere because the southern continents do not extend sufficiently poleward to reach the latitudes in which this type occurs. The forest is characterized by its predominantly coniferous tree growth and its very limited number of tree species.

In North America the boreal forest extends from the Bering Sea coast of Alaska southeastward approximately 4400 miles to the Atlantic shores of southern New Brunswick. Its latitudinal breadth of approximately 24 degrees ranges from around 69 degrees in the lower Mackenzie valley to around 45 degrees in northern New England. In Eurasia it extends eastward from the Fiord coast of Norway to the Pacific shores of Siberia, a distance of more than 5000 miles. Here the latitudinal breadth ranges some 30 degrees from about 72 degrees in the lower Katanga Valley to approximately 42 degrees on northern Hokkaido Island of Japan.

The dominant tree species throughout this tremendous range are primarily limited to spruce, fir, larch, and pine occasionally interspersed with aspen, paper birch and related species which temporarily occupy areas subjected to fire or other disturbance. Draped lichens are frequently prominent on all conifers. Ground covers of mosses, lichens, ferns, and low shrubs are common throughout. In this microthermal climate vegetation decomposition is extremely slow. Bogs, muskegs, and lowland swamps containing decayed and decaying vegetation are common throughout the entire type, generally increasing in frequency and extent from the southern to the northern limits. Peet beds on the more well-drained soils are also common. At the northern limits of the boreal forest type it fingers out into the adjoining tundra and in many areas becomes an open woodland tundra which, for the most part, will be treated as tundra in the next section.

Climatically the boreal forest is characterized by short, rather warm summers and long, severe winters with a rapid transition from one to the other in spring and fall. Mean summer temperatures rise to more than 50 degrees for at least one month and usually prevail from three to four months each season. Winter temperatures below freezing, on the other hand, prevail from 5 to 7 months and many stations record sub-zero averages for several months during the season. The general climatic type may thus be classified as microthermal snow forest climate (D). The climates of both continents are predominantly continental. On both their east and west extremities, however, moderating maritime air tends to modify the extremes between summer warmth and winter cold. Precipitation also varies considerably in amount between interior and coastal stations. Total annual precipitation of 10 to 20 inches is characteristic of the interior sections while in milder areas near the sea and in closer proximity to rain-bearing storms it may amount to 20 to 30 inches or more. In all cases summer is the season of greatest intensity. The variations brought about by these differences require the addition of one or another of the subtype climatic designations in various parts of the boreal forest area. Much of the summer precipitation, especially in interior regions, occurs in the form of convective thundershowers.

The long summer days, often with comparatively low relative humidities, large quantities of quickly dried out lichens and mosses, and the highly flammable coniferous vegetation make much of the boreal forest a definite fire-prone type in spite of the maximum summer precipitation. The precipitation also varies considerably by years so that many summers, even though showing a maximum precipitation, are in fact relatively dry. The crowning potential is usually high and spot fires resulting from burning lightweight spruce cones and flammable peeling bark of the paper birch are frequent.

The blowdown potential of the boreal forest is particularly high in many areas because of shallow or otherwise poorly anchored root systems. Blowdown debris adds materially to burnable fuels already on the ground.

TUNDRA. The tundra of North America and Eurasia is a nearly treeless zone of transition between wooded tracts of the boreal forest on the south and the barren polar icecap on the north. It is a region of rolling to nearly level terrain generally less than 1500 feet above sea level. Like the boreal forest, this type is confined primarily to the Northern Hemisphere with the exception of limited areas at elevations above the tree line in some of the world's major mountain chains. For purposes of this text the latter are considered of no particular operational significance.

The North American tundra extends from the Alaskan shores of the Bering Sea to the coast of Labrador. Beginning in the Aleutian Islands the type follows the western and northern Alaskan shores in a belt generally from 100 to 200 miles wide to the delta of the Mackenzie River. Beyond there it expands in an ever-widening belt northeastward across the islands in the Canadian Archipelago and the coastal lowland of Greenland and southeastward around Hudson Bay to the coast of Central Labrador. It extends from James Bay at 55 degrees to the northern tip of Greenland at around 83 degrees north latitude.

The tundra occurs on all of the coastal lowlands of the islands of the North Atlantic ocean and those reasonably adjacent to northern Europe and Siberia. On the Eurasian mainland it is a virtually continuous belt from the north coast of Norway to the Siberian coast of the Bering Sea. The type thus nearly encloses the polar icecap, the Artic Ocean, and Greenland.

The Eurasian tundra is narrower than that of North America and is confined to higher latitudes primarily north of 65 degrees. It is generally less than 100 miles in width except in the vicinity of the mouth of the Ob River and eastward for 400 to 500 miles where it attains its maximum width of 300 to 400 miles. Along the northeast coast of Siberia it occurs in spotty patches from Bering Straits to the Kamchatka peninsula. Because of the occasional mountainous topography and river systems of Siberia, it is somewhat difficult to locate any definite southern boundary of the type.

Vegetation of the tundra is characterized throughout by its low-growth habit. However, in all it presents several types of landscapes. Rocky barrens are common in the northern portions which bear little or no vegetation. These are the result of both earlier glacial scouring where exposed bedrock stands elevated above the surrounding low terrain, and to annual grinding beneath moving masses of water-borne ice along the low-lying shores. A virtually complete plant cover is characteristic of the remaining tundra area. On the drier, better drained areas moss and lichen perhaps 1 to 2 feet high form dense growths in which nothing else may be seen from one horizon to the other. In many of these areas flowering herbs, grasses, and prostate shrubs are submerged in this deep carpet. On low and wetter ground the moss-lichen type merges gradually into the dwarf shrub tundra. This type consists of several varieties of woody plants both deciduous and evergreen that grow extensively, but rarely more than knee deep, beneath which a thick, damp, resilient carpet of the moss-lichen still persists. In other parts there is a wooded tundra. This is distinguished from the truly treeless tundra by the presence of many, though widely scattered trees individually or in clumps. Both coniferous and broadleaf deciduous trees are represented. They stand erect though not very tall. The wooded tundra is distinct from the boreal forest tundra margin in that a much larger percentage of its area is occupied by the moss-lichen-shrub forms than by the trees. In fact, the tree forms are confined primarily to stream valleys and other protected depressions. The shrub-moss-lichen formation is usually present as undergrowth. Other significant landscape features include occasional sedge-grass meadows and innumerable bogs, marshes, lakes and rivers. The thousands of lakes and rivers are often connected in a complex disrupted drainage pattern defined by the ancient continental glaciation. They are abundant in the tundra regions of both North America and Eurasia.

The climate of the tundra region is characterized by long, intensely cold winters and short cool summers. It is a region of permafrost frozen solid from the surface downward in the wintertime and thawing to a depth of a few inches up to 2 to 3 feet in different parts of the type during the summer months. The general climate type is tundra climate (ET); during the warmest month the temperature is below 50 degrees but above 32 degrees Fahrenheit. Average annual precipitation varies regionally from about 3 inches up to about 20 inches depending upon the dominance of continental or maritime air masses and variations in common storm tracks. At some stations the highest rainfall occurs in the summer while at others the maximum precipitation occurs in winter. One significant feature of the tundra climate is its extreme variability. Some regions that are characterized by maximum summer precipitation, for example, may experience negligible spring and summer rain.

The dominance of the lichen-moss formation makes the region as a whole fire prone during the short summers. These plants, being hydroscopic, dry out to the flammability point after even a few days of reasonably low relative humidity, a frequent summer characteristic of the region as a whole.

Blowdown has no significance in the tundra.

7.5.2 Distribution of Forest and Climate Types

The principal worldwide distribution of forest and climate types is illustrated in Figures 7-4 to 7-8.

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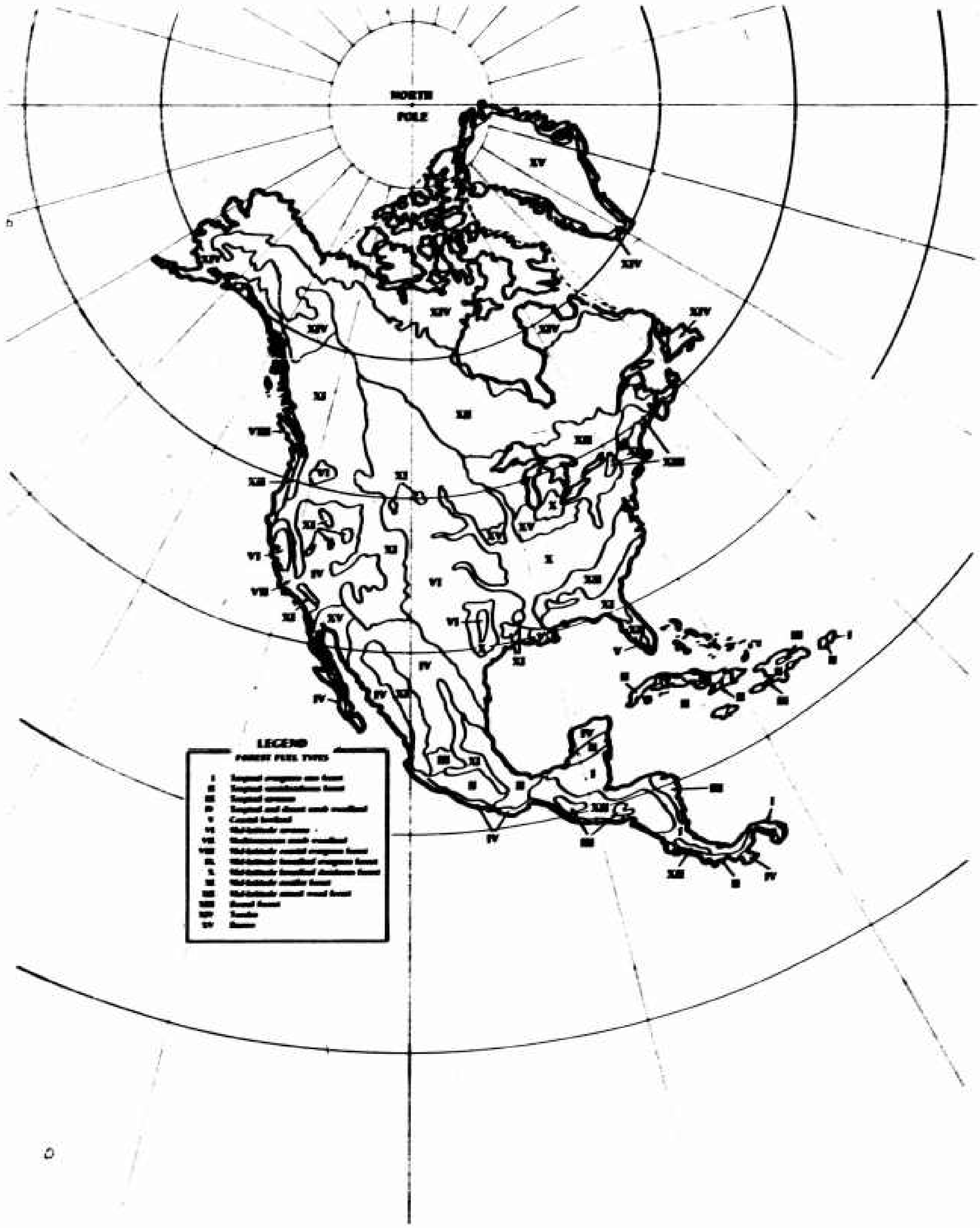

Figure 7-4A. Forest fuel types of North and Central America.

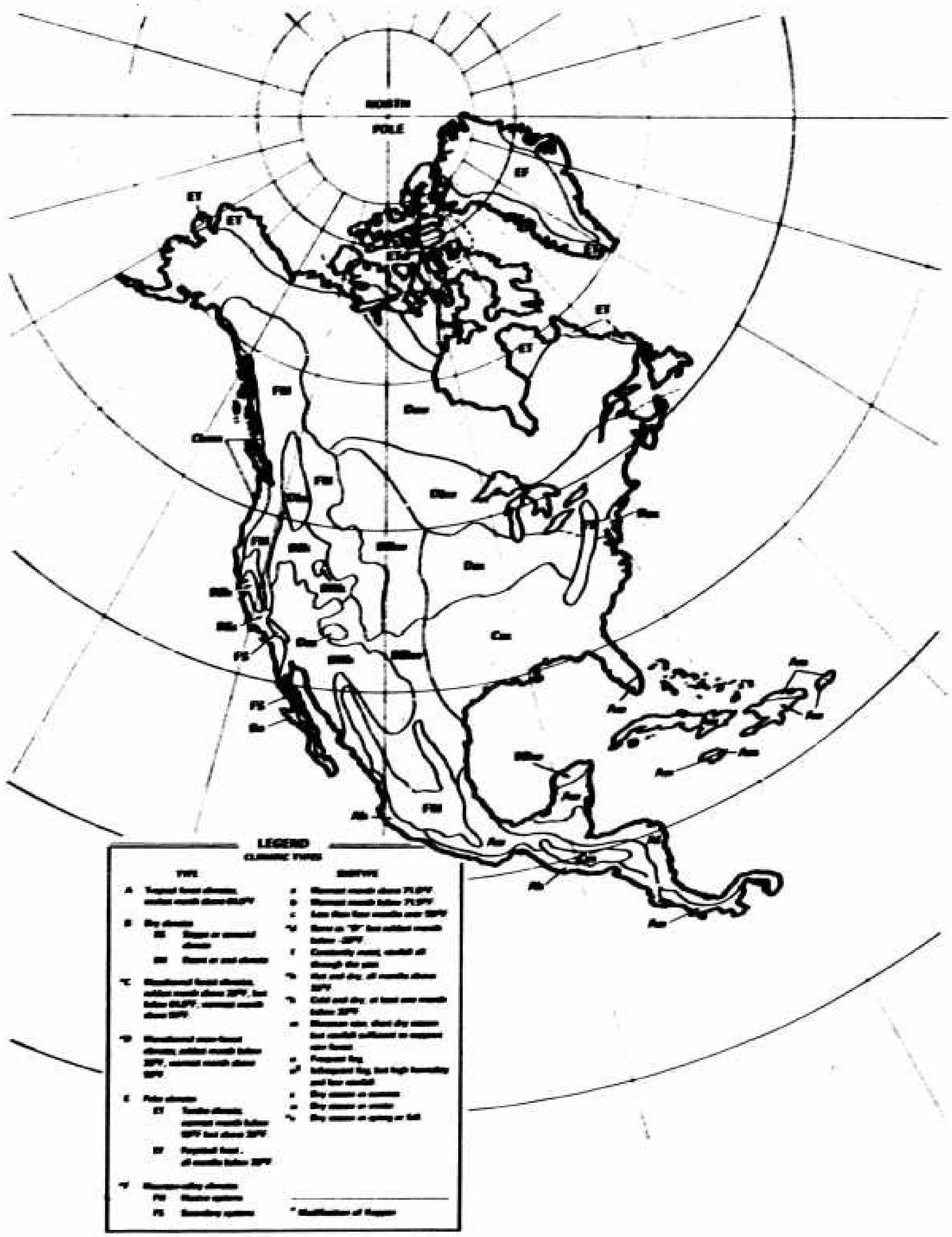

Figure 7–48. Climatic types of North and Central America.

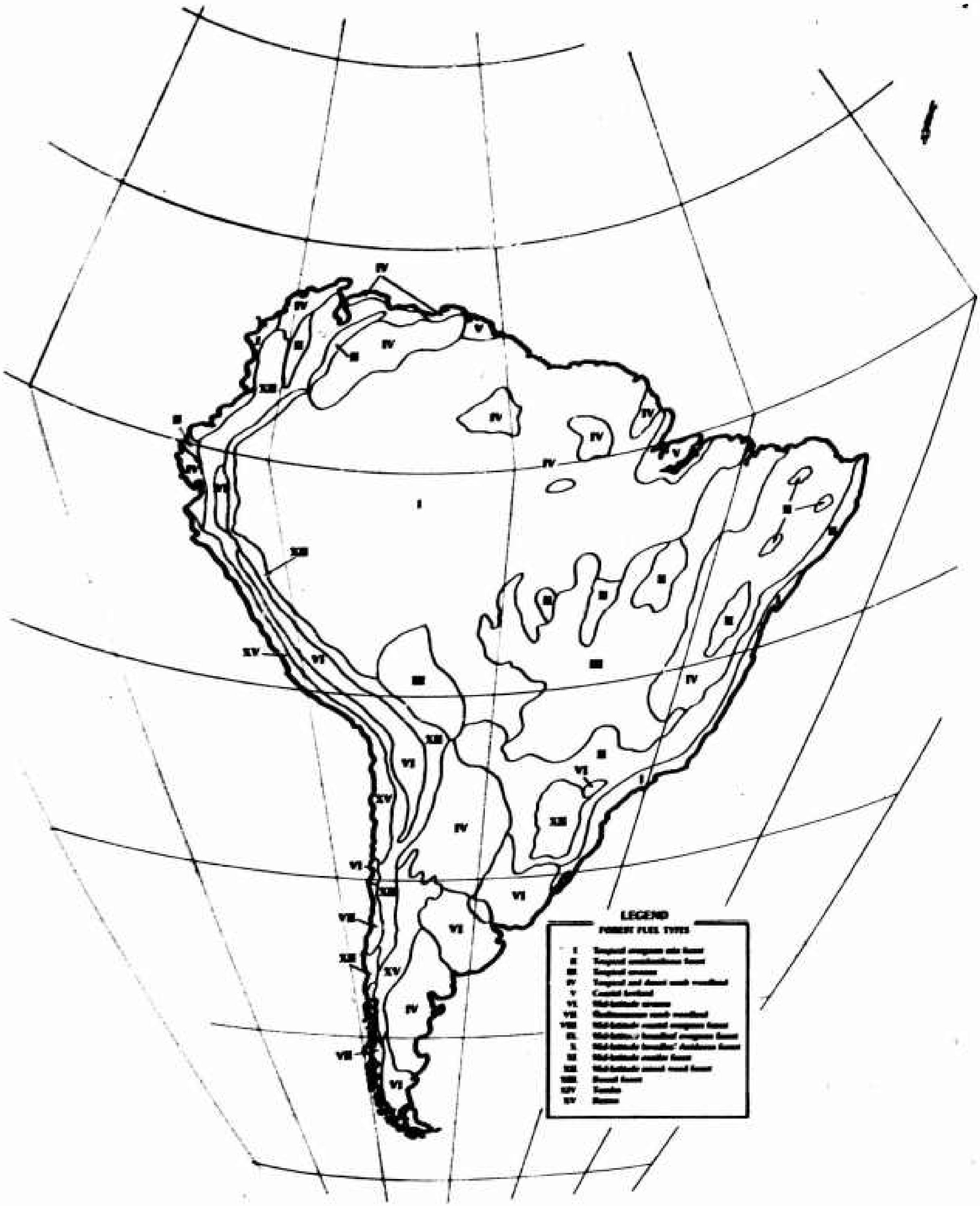

Figure 7-5A. Forest fueld types of South America.

Figure 7-5B. Climatic types of South America.

Figure 7-6A. Forest fuel types of Eurasia and the Philippines.

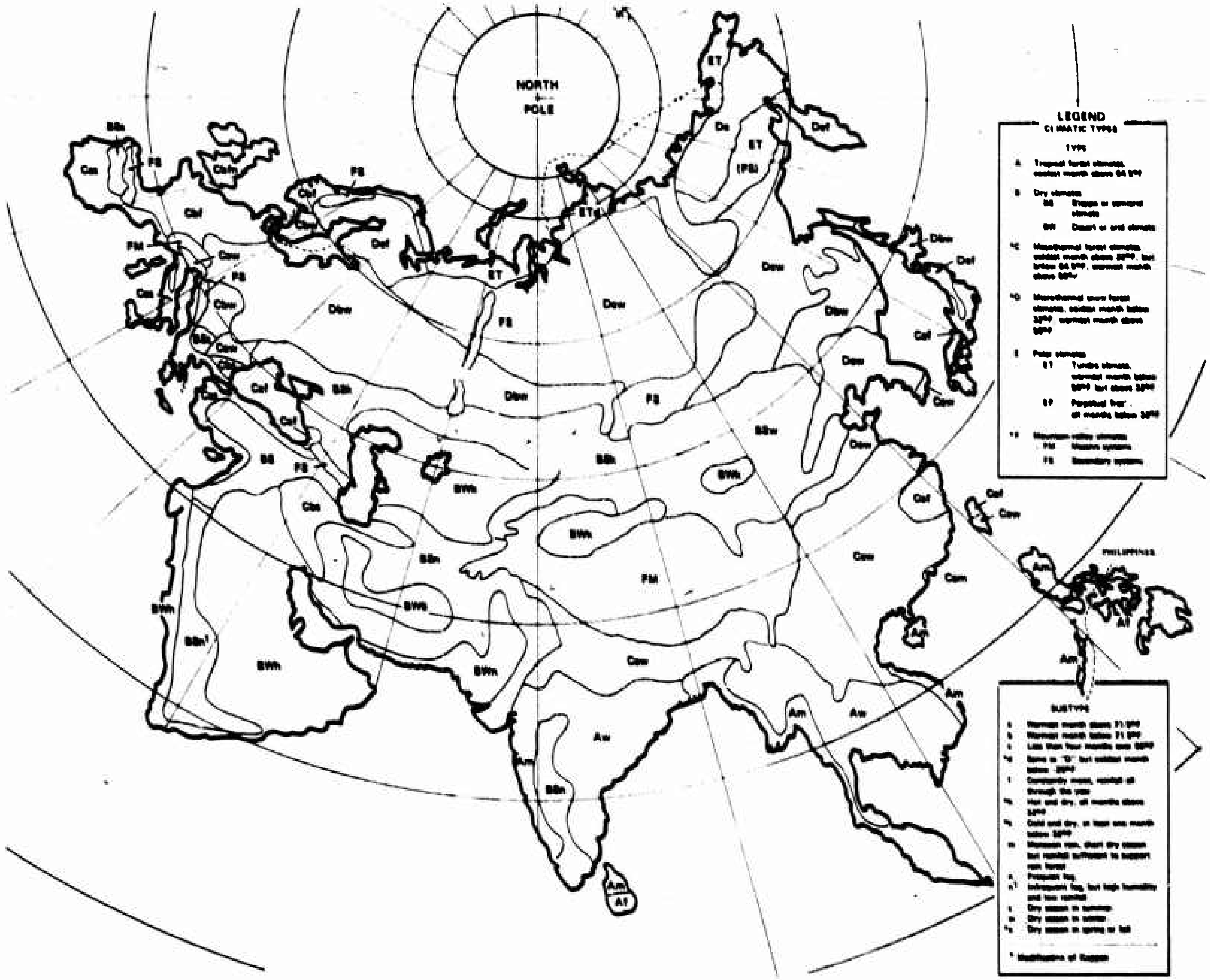

Figure 7–6B. Climatic types of Eurasia and the Philippines.

Figure 7-7A. Forest fuel types of Africa.

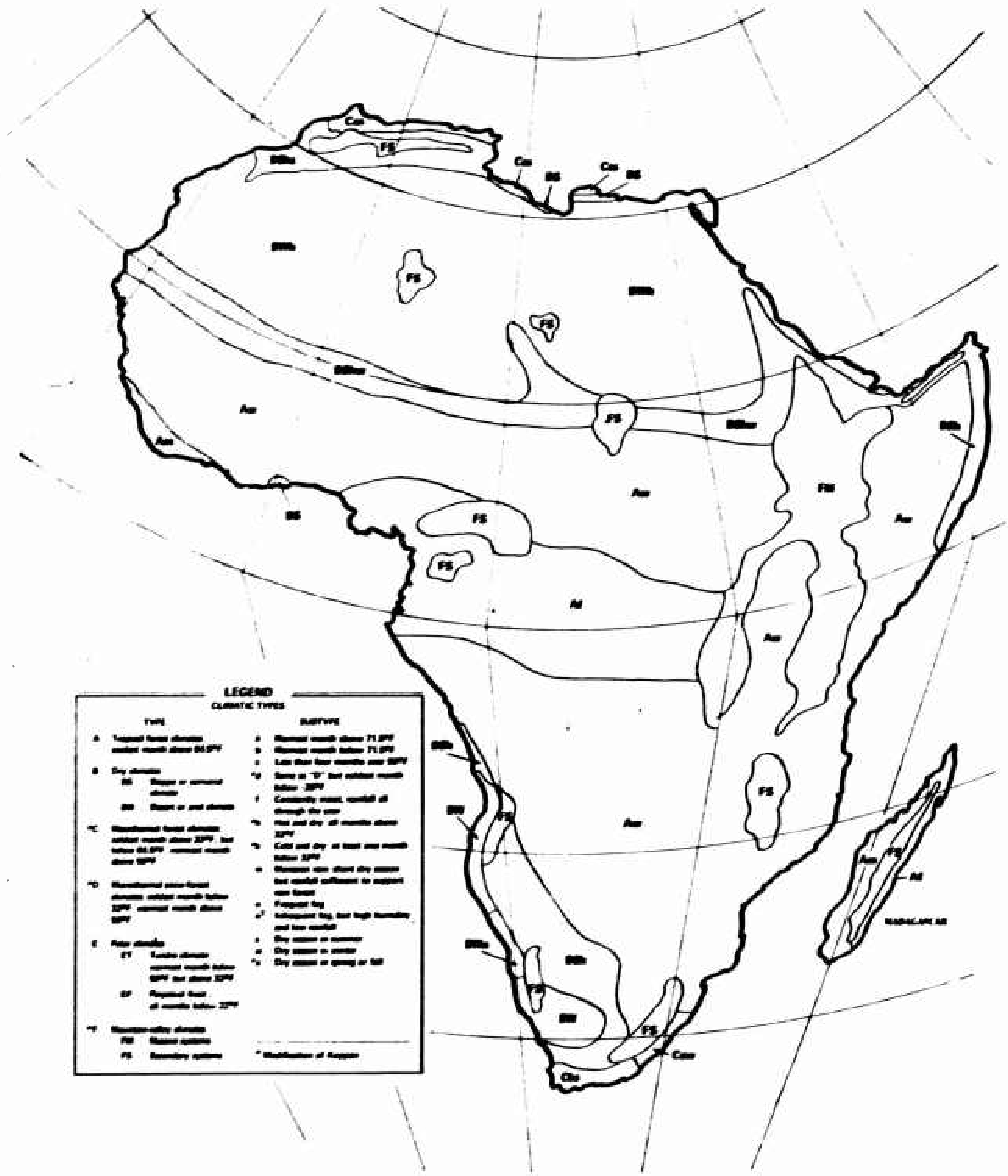

Figure 7-7B. Climatic types of Africa.

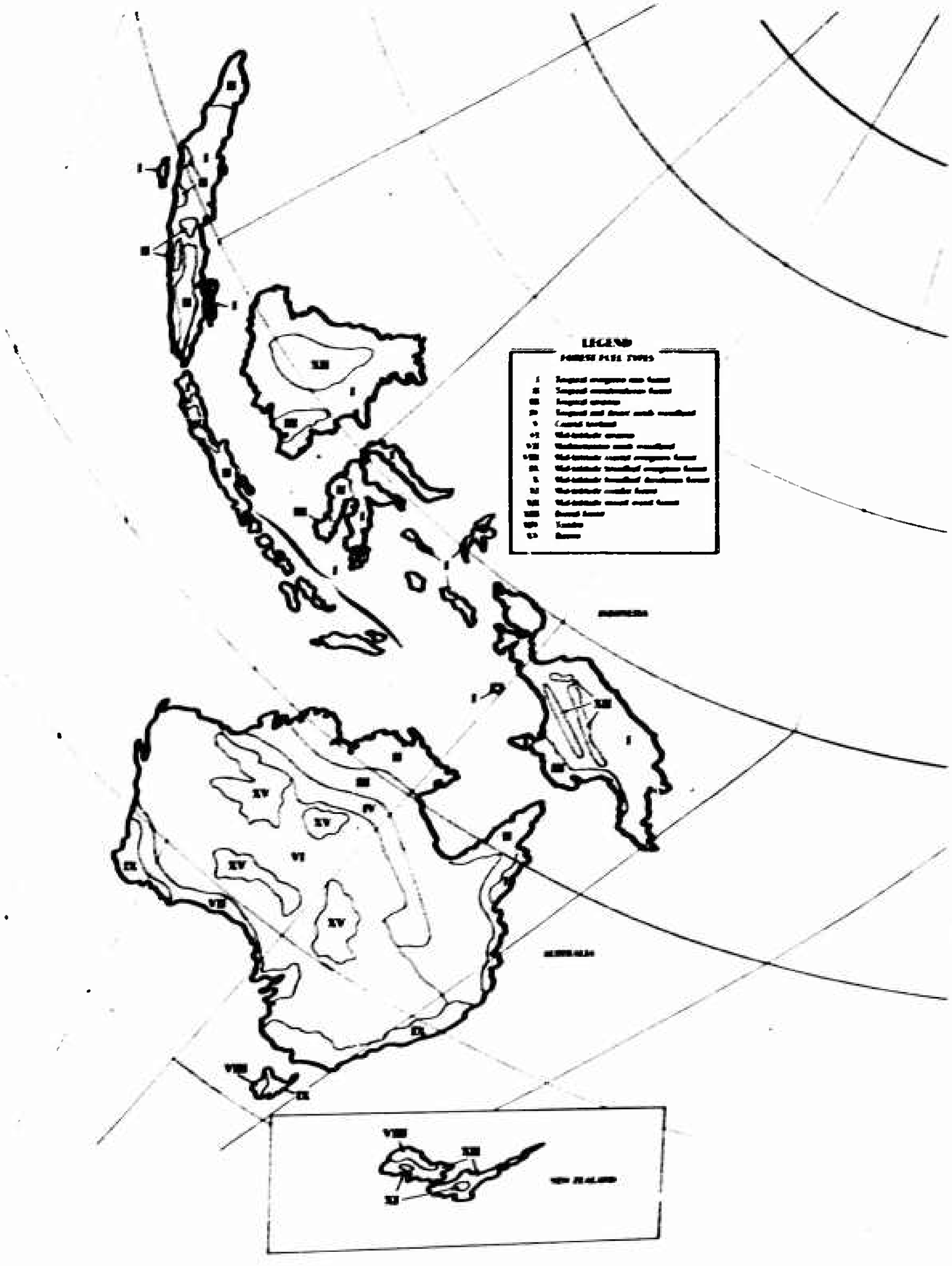

Figure 7-8A. Forest fuel types of Australia, New Zealand, and Indonesia.

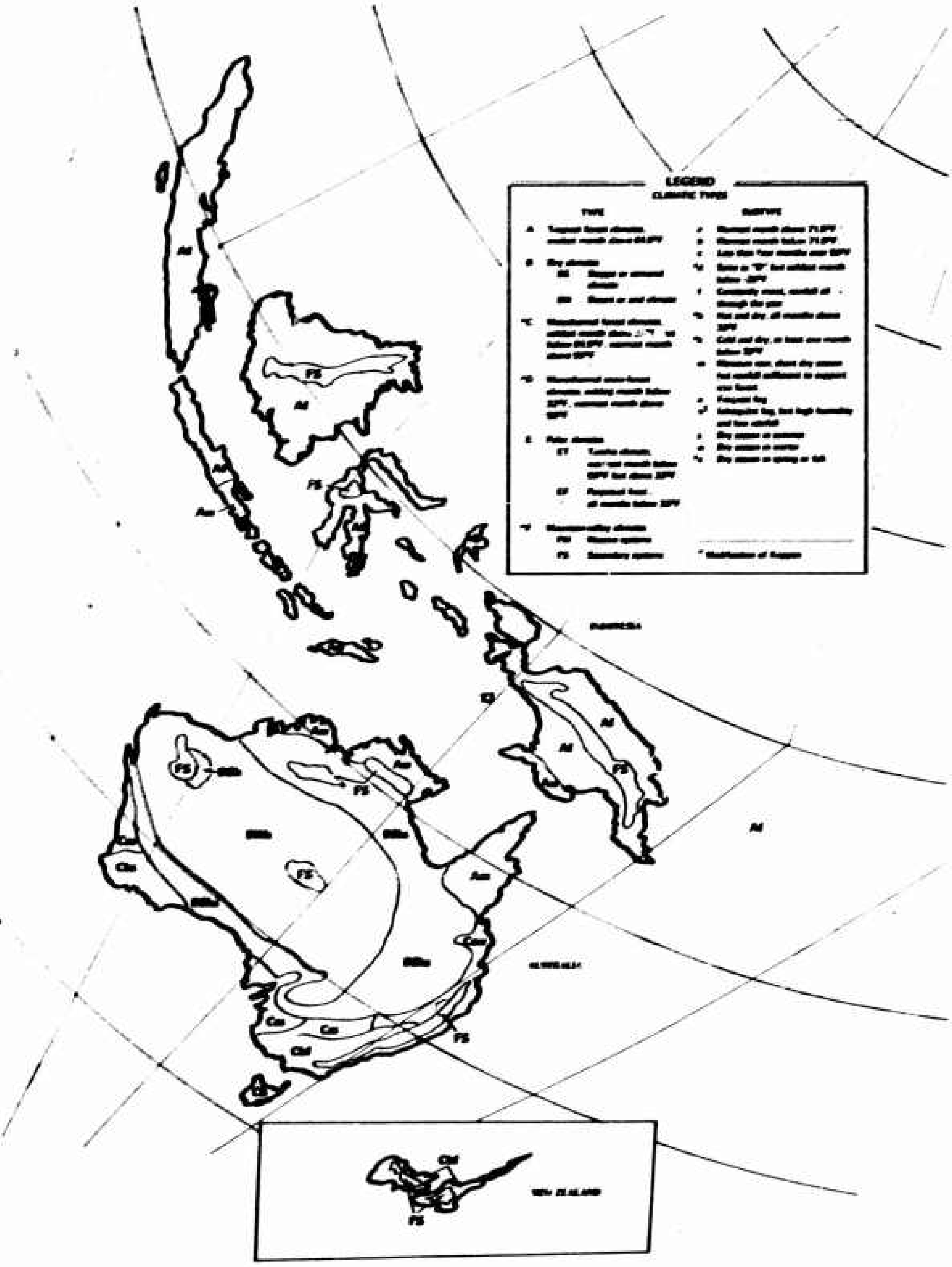

Figure 7-88. Climatic types of Australia, New Zealand, and Indonesia.

CHAPTER 8

WEATHER, FUEL MOISTURE AND TOPOGRAPHY

8.1 CLIMATE AND WEATHER

Climate can be defined broadly as the aggregate of the weather as revealed by past experience. For example, it includes such measures of the lower atmosphere as the temperature, winds, atmospheric moisture, cloudiness, precipitation, and air pressures that have prevailed during any considerable period of years. It is compiled in such ways as to indicate the average annual or seasonal values of these measures or the normal frequencies of particular weather events. Weather, on the other hand, is a measure of the dynamic behavior of the atmosphere at a given time and place or over a continuum of time at that place. Measures of weather must, of course, include those which can be averaged over a long period of time to describe in many different ways depending on the ways in which they are to be used. These may include such things as crop production, manufacturing and transportation industries, major public events or even military operations. The concern for purposes herein is with fire weather.

8.1.1 Climate

Climate, as treated in Chapter 7, deals with long-term weather measurements that determine, in part, the kinds of vegetation which may grow in a region and the average periods of the year in which that vegetation may be susceptible to ignition and burning as a result of nuclear detonations. The climatic data also provide a reasonable clue to the accumulation of leaf litter and deadwood on the forest floor within these regions.

8.1.2 Weather

Weather with respect to forest fire is called fire weather. It consists of measures of the atmosphere having to do with the season, the week, the hour, and instant which determine, at any time, the relative likelihood that fires will start and burn.

8.2 WEATHER AND FIRE POTENTIAL

The fire potential of any forest depends upon its flammability defined as the relative ease with which it can ignite and burn. The flammability of both dead and living components of the vegetation is important in this regard, but because of different relationships to weather, dead and living fuels will first be discussed separately.

8.2.1 Dead Fuels

8.2.2 Weather and Ignitability

Since living fuels have already been largely eliminated as possible sources of ignition from thermal radiation, this discussion will be limited primarily to the tinder fuels listed in Chapter 6. These differ in their susceptibility to thermal ignition because of their inherent differences in physical and chemical structures. However, any one of these fuel elements differs, furthermore, in its susceptibility to ignition according to its moisture content. The significance of these relations has been discussed in Chapter 4. Moisture content is defined in this sense as a percentage. It is determined as the weight of water contained in a fuel element divided by the oven-dry weight of the fuel multiplied by 100.

When a plant part dies, food manufacturing and growth stop and water circulation ceases. The contained water then evaporates until the dead tissues become "air dry." The amount of water remaining is quite variable and is always changing, depending on how wet or dry the environment happens to be. Sustained fire ignition in dead tinder fuels appears to be in the region of less than approximately 30 percent moisture content. Fuel surfaces wetter than this are thus not expected to maintain sustained ignitions while those below this value may be susceptible to varying degrees.

Dead vegetation retains its original structure of cells, inner cellular spaces, and capillaries. It can soak up liquid water like a blotter, although more slowly, until all these spaces are filled. In the wetting process dead vegetation may thus hold three or more times its own dry weight in water. Fine materials and the very surface layers of larger substances may absorb that much water in a matter of minutes while the interiors of large logs, for example, may require a season or more of heavy precipitation.

A second and equally important consideration in our understanding of fuel-wetting processes is the fact that the fibers making up the dead cell walls are hygroscopic. Hygroscopic materials not already saturated have an affinity for moisture which makes it possible for them to adsorb water vapor from moist air. This process is one of molecular attraction.

Molecules of water are attracted and held to the cell walls by the hygroscopic character of the fibers which reduces the vapor pressure of the water attracted to them. Added layers of attracted moisture have progressively weaker bonds until the cell walls become saturated. In an atmosphere of 100-percent relative humidity the vapor pressure in the outer layer of water on the cell wall is equal to that of free water or saturation pressure. The amount of bound water at the fiber saturation point varies with different materials, but for most of them which are of concern here, it is in the range of about 30 to 35 percent of the fuel dry weight. Consequently, this is at the upper limit of expected fuel ignitability.

Any addition of moisture to the fuel must be deposited on the fuel surface in the form of free water as precipitation or as heavy dew. Either of these processes can quickly render tinder fuels relatively unignitable.

Wetting processes that render fuels unignitable are important, but the drying processes that bring fuels within the range of ignitability and the combination of processes which cause fuel moisture to rise and fall within this range are even more critical in determining fire potential.

Dead fuels that have been thoroughtly dampened from free water within and on the surface lose their moisture in a drying atmosphere in essentially two steps. The first step is that of simple evaporation as from any free water surface. In this step the rate of moisture decrease is directly proportional to the deficit of relative humidity in the atmosphere below 100 percent and on surface wind that dissipates the evaporated moisture in the surrounding air. This process actually slows down as free water disappears from the surface but here this step will consider moisture loss as a linear function of humidity and time. The second step begins when the fuel surface has reached the fiber saturation point after which the hygroscopic nature of the dead fuel becomes dominant in the drying process (Reference 1).

The second period of drying depends upon an outward gradient between the adsorbed water vapor pressure and the ambient vapor pressure in the atmosphere. As moisture removal progresses below the fiber saturation point, the adsorbed water vapor pressure gradually declines and the vapor pressure gradient within the fuel element is reduced accordingly. Either of two conditions must prevail to assure continued significant drying. One is to maintain a surrounding vapor pressure appreciably below the declining adsorbed water vapor pressure; the other is addition of heat to the fuel at a rate that will increase its temperature and correspondingly its contained water vapor pressure. Both processes operate in nature sometimes augmenting and sometimes opposing each other. As drying progresses toward lower moisture contents, the vapor pressure gradient established within the fuel element becomes dominant over that which exists between the fuel surface and the atmosphere. Windspeed during this stage becomes much less important and has little practical significance.

In the range of moisture content below fiber saturation an important concept is that of equilibrium moisture content. Fuel will either gain or lose moisture within the range of fiber saturation down to about 2 percent according to the relative states of the fuel and its environment. The amount, rate, and direction of moisture exchange depend on the gradient between the vapor pressure of the water in the fuel and the vapor pressure in the surrounding air. If there is no gradient there is no net exchange and a state of equilibrium exists.

The atmospheric vapor pressure is dependent upon the temperature and moisture content of the air. The vapor pressure of the water in the fuel depends upon the fuel temperature and moisture content. If the vapor pressures are the same, then for any combination of temperature and humidity in the atmosphere, there is an equilibrium fuel moisture content. This almost but does not quite exist in nature. Small vapor pressure differences can and do exist without further moisture exchange. Some additional energy is required to bring about exact balance.

Equilibrium moisture contents have been determined in the laboratory for numerous hydroscopic materials including a variety of forest fuels (References 2, 3). The usual procedure is to place the material in an environment of constant temperature and humidity, leaving it there until the moisture content approaches a constant value. The process in then repeated over the common ranges of humidity and temperature encountered in nature. Continuous or periodic weighing shows the changing rates at which equilibrium is approached from both directions. Different fuel types usually have different equilibrium moisture contents, but for most fire weather purposes it is satisfactory to use the average determined for a number of fuels. Note particularly in Figure 8-1 that equilibrium moisture content values obtained in wetting and drying are not the same.

The equilibrium moisture content shown as an average for six fuel types is dependent mainly on relative humidity, whether the fuel is wetting or drying, and to a smaller extent on temperature.

The rates at which moisture content approaches equilibrium vary not only by the kind of fuel material, but with other characteristics such as fuel size, shape, and chemistry, and the compactness or degree of aeration of the mass of fuel particles. With moisture content below fiber saturation, the rate of wetting or drying by vapor exchange slows down as the difference between the actual moisture content and the equilibrium moisture content for the environmental conditions of the moment decreases. This relationship indicates that moisture content approaches equilibrium at a continuously decreasing rate. For the tinder fuels considered important to ignition, however, the rate of equilibrium attainment in general can be considered fast enough that after an hour or two of reasonable stable temperature and humidity the fuel will be at or near its equilibrium moisture content.

However, at this point it is important that another consideration be brought to bear. In laboratory determinations of equilibrium moisture content, for example, it is assumed that the temperature of the sample of material and that of the control chamber are the same. In field applications atmospheric temperature and humidity are measured at some standard height, usually 4.5 feet. Where fuels on the surface are shaded by the forest canopy or by clouds, it can be assumed for most purposes that the fuel temperature and the immediate surrounding environment are the same as those measured. Where fuels are exposed directly to the sun those on or near the surface may attain temperatures vastly greater than those measured (Reference 4). This must be taken into account when estimating equilibrium moisture contents. This same relationship should be considered during the first stage of drying down to fiber saturation point. Figure 8-2 illustrates fine fuel equilibrium moisture contents in relation to measured weather. The second stage of drying, the stage below the fiber saturation point, begins when the fuel surface no longer feels damp to the touch.

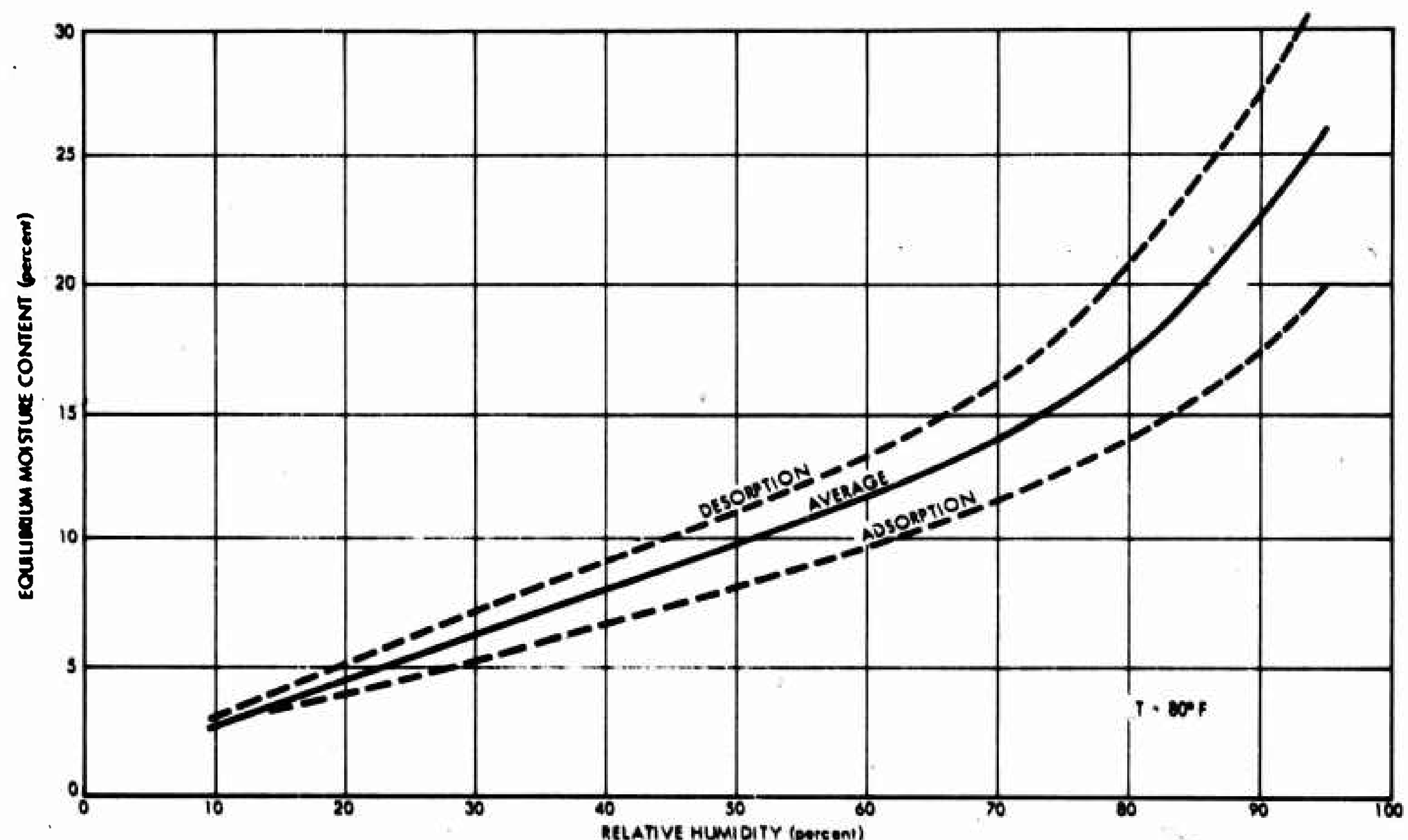

Figure 8-1. Average equilibrium moisture content for a number of common forest litter fuels.

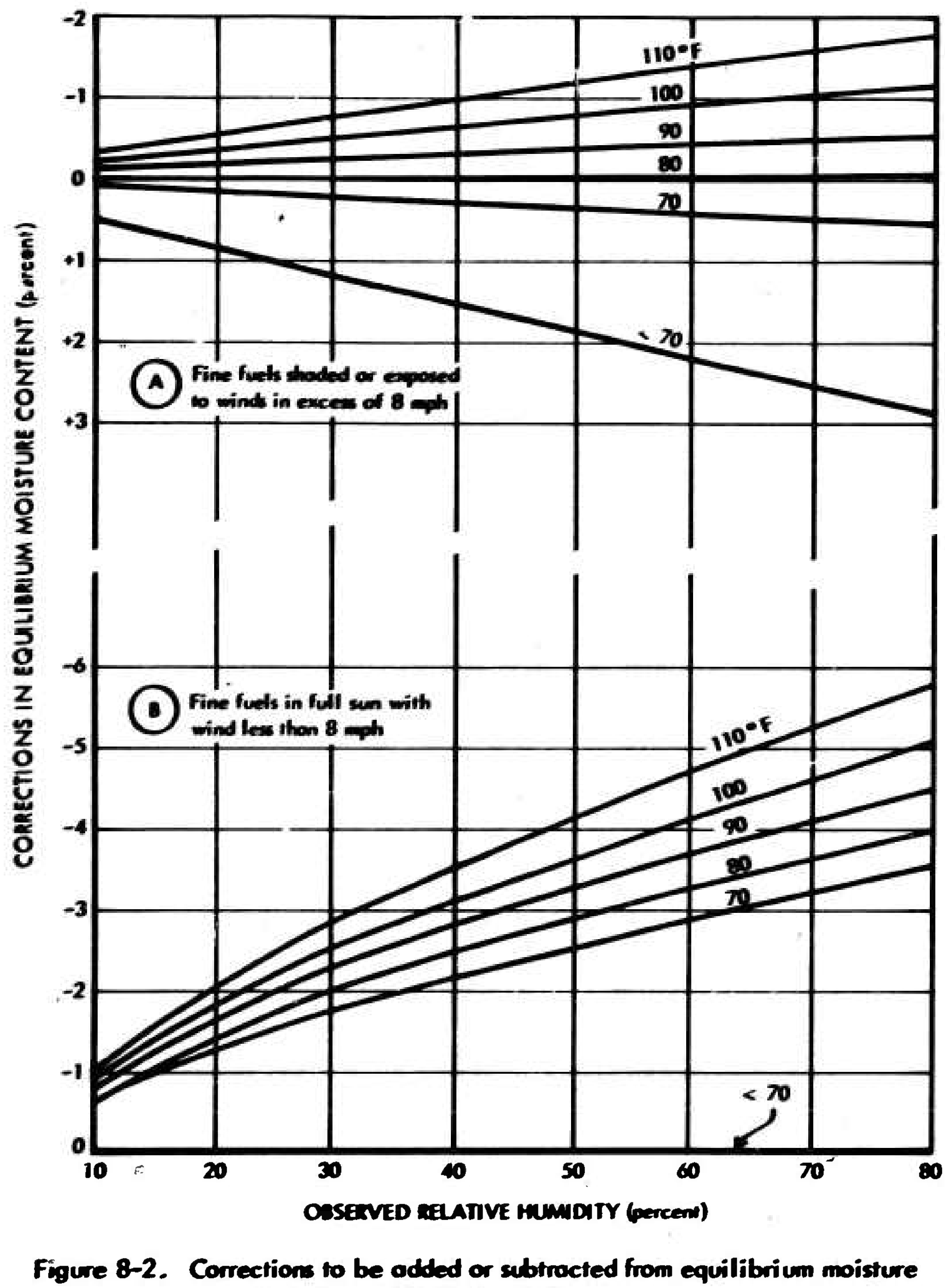

Figure 8-2. Corrections to be added or subtracted from equilibrium moisture contents indicated in Figure 8-1.

Use of the equilibrium moisture content concept makes it possible to estimate whether any fuel moisture is increasing or decreasing under a particular environmental situation indicative of moisture stress in the direction of equilibrium. This is reasonably satisfactory for the tinder fuels generally considered ignitable by the thermal pulse. However, as will be shown later, by itself this is a poor indicator of the quantitative rate of moisture content change in kindling or larger materials.

8.2.3 Weather and Fire Spread

The same principles apply to determination of fire spread flammability of dead kindling and larger fuels in relation to weather as for ignition. The difference is in the matter of degree.

Fire ignition is virtually a surface phenomenon in tinder fuels in which internal moisture gradients are quickly reduced to relatively small amounts. The major exception to this is in rotten wood, but here the low thermal and mass transfer characteristics of the material tend to isolate the surface from the interior. Fire spread, on the other hand, is concerned with the progressive horizontal and vertical involvement of larger and larger single fuel elements. In both these cases the lag in time between actual and equilibrium moisture content for the environment of the moment is long. For these reasons saturation within a day and thereafter follow equilibrium moisture content closely while larger or deeper fuels may require days or weeks to become burnable.

A highly important consideration with respect to the wetting and drying equilibrium moisture content curves of Figure 8-1 is the relative rates at which equilibrium is approached from the two directions. The data presented in Table 8-1 were determined in the laboratory for sets of similar fuels of different thicknesses exposed to both wetting and drying regimes. First, the fuels in equilibrium moisture content with 80 degrees Fahrenheit and 80 percent relative humidity were placed in an environment of 80 degrees Fahrenheit and 20 percent relative humidity. Next, these fuels at the lower equilibrium moisture content were exposed to an environment of 80 degrees Fahrenheit and 80-percent relative humidity. The tabulation compares the times required to approach equilibrium in the two cases (Reference 5).

Table 8-1. Equilibrium moisture content timelag.

Fuel	Time Required to Reach Equilibrium	
	Drying	Wetting
	(hours)	(hours)
Grass	1/2	3/4
Broadleaf Leaves	4	5
Conifer Needles	5	7
1/2-inch Twigs	25	30

These data are interpreted to mean that fuels exposed to a normal diurnal relative humidity cycle of equal duration of wetting and drying regimes will dry out more in the daytime than they will recover at night. As a consequence, during a sequence of similar days there will be progressive drying from one day to the next in all fuels larger than those considered as tinder. Use is made of this phenomenon in the next section estimating dead fuel moisture contents.

Internal moisture gradients which may persist in the heavier fuels over prolonged periods determine, to a major extent, the depth to which fire will penetrate these fuels and thus regulate the relative amount of fuel available for combustion. This affects both fire spread and fire intensity. How this lag operates is further illustrated by the diurnal moisture behavior of a 1/2-inch cylinder of sound wood exposed under a fluctuating wetting and drying environment, Figure 8-3.

If this 1/2-inch thick material were to be considered as a 1/2 inch outside sheath surrounding a 12- to 18-inch log, its diurnal moisture content change would be damped by the moisture content of the interior of the log. For example, if the log as a whole started out with a higher moisture content at the beginning of a drying period, the external and central moisture contents would go somewhat higher at night while the interior moisture content would gradually decrease. The internal moisture gradients in solid materials are difficult to measure with present technology but have been determined in enough cases to indicate the general processes involved, Figure 8-4 (Reference 6).

Guidelines for estimating forest flammability based on dead fuel moisture content as modified by living fuels are described in Section 8.4.3.

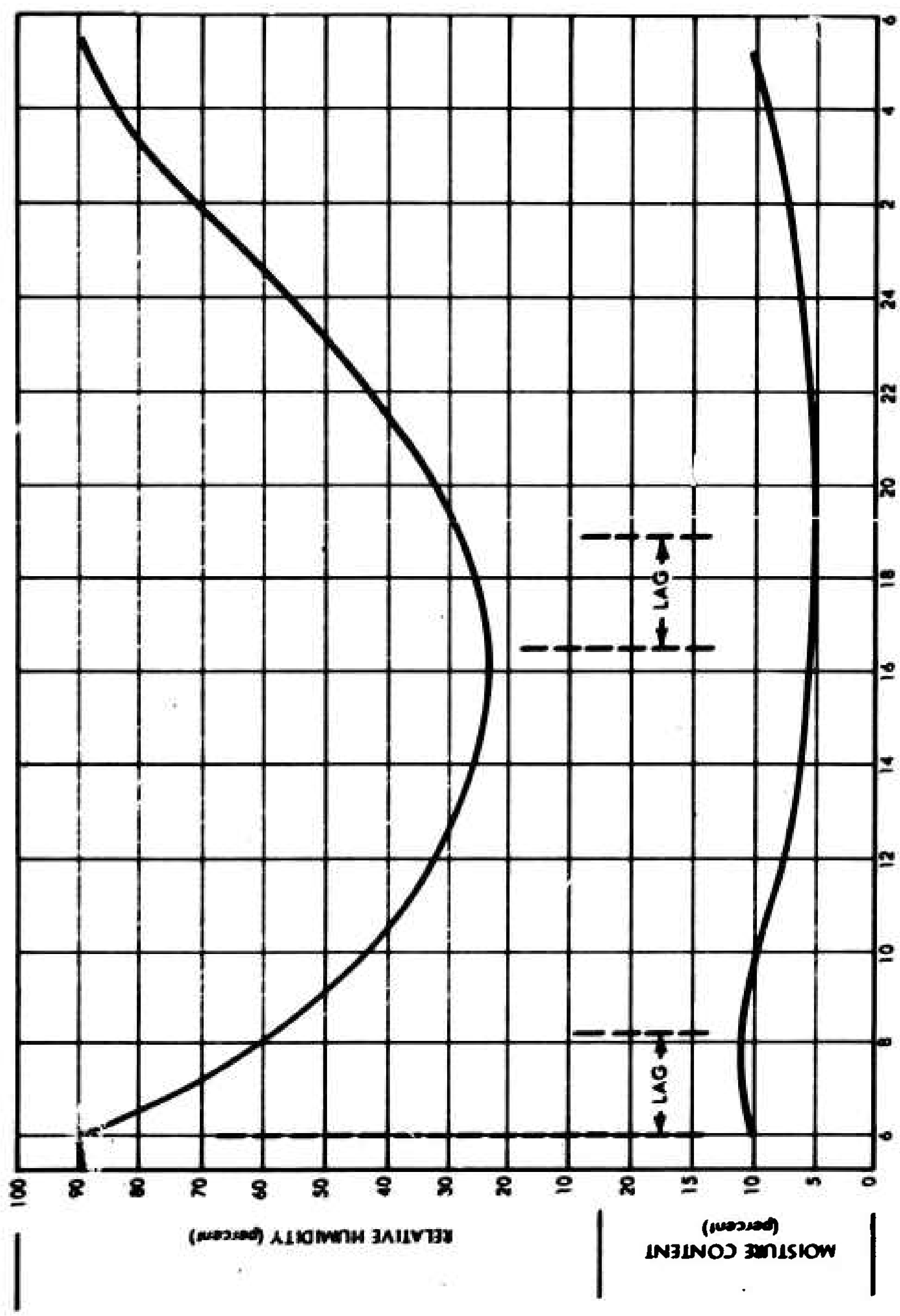

Figure 8-3. Lag in 1/2" wood cylinder moisture content behind fluctuating relative humidity.

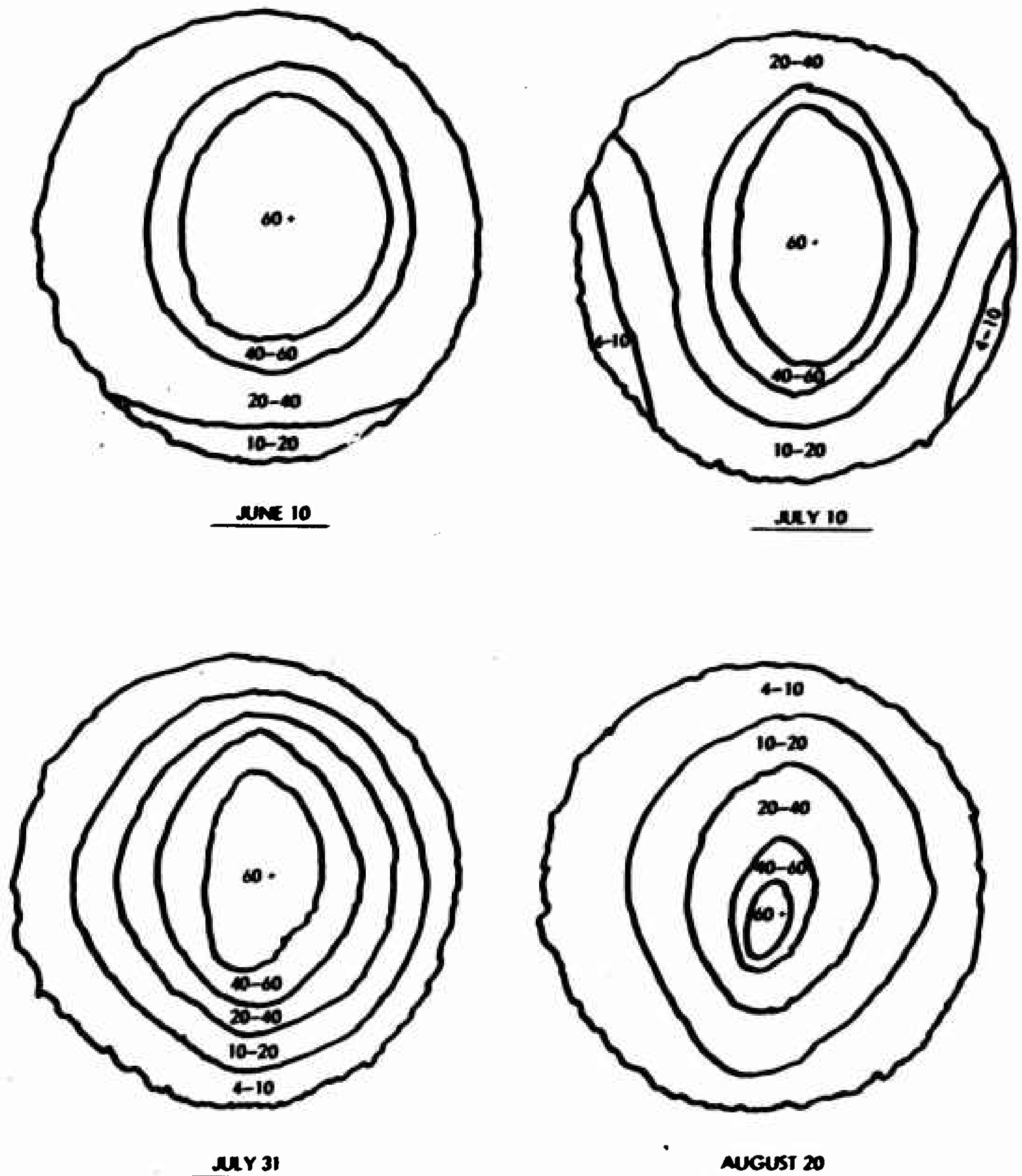

Figure 8-4. Log moisture contents under a drying regime (numbers are moisture content percent).

8.2.4 Living Fuels

Living vegetation with the exception of lichens is not a tinder fuel. With this one exception, its effects are therefore confined to its flammability with respect to fire spread. For this purpose, living fuels can be defined as the living foliage and supporting stems of grasses and herbs, the green leaves of trees and shrubs, in some cases the finer supporting twigs of the current year's growth, and cross-linked filament bodies of lichens. Weather affects flammability of these living fuels in general in two ways. It determines the beginning and ending dates of the growing season; within the growing season, it regulates both living fuel chemical and moisture contents.

8.2.5 Differences in Vegetation Types

The living foliage of virtually all vegetation except tropical rain forest vegetation responds to both seasonal and short-term weather-controlled environments. But at the same time it is necessary to make some distinctions between some of the broad climate-associated vegetation classes relating to their relative flammabilities. A few examples will suffice.

The first segregation is between tree and shrub foliage that may enhance fire thermal output and those which tend to depress it. Differences in selected groups of vegetation can be most readily summarized in tabular form while, at the same time, indicating their relative sensitivities to changing fuel moisture with short-term weather changes within the normal growing season.

Table 8-2 permits an immediate separation of nonflammable living foliage from that which adds to forest fuel at least through part of the year. Within the latter vegetation groups, however, it is also to be noted that there are some variations in weather controlled in-season moisture relations. Some typical seasonal moisture and flammability behavior patterns are indicated in Figures 8-5 to 8-8.

New foliage of all vegetation species has its maximum moisture content and lowest flammability upon emergence, with gradually declining moisture content and increasing flammability as the growing season progresses. Evergreen species, by definition, retain at least part of their living foliage through dormant seasons with minimum moisture contents outside of the moist tropics. Even though this older foliage may increase somewhat in moisture content at the end of dormancy, nevertheless, it has a strong modifying influence

Table 8-2. Contribution of living fuel to fire thermal output and variability with short term weather changes.

FUEL	OUTPUT	IN-SEASON WEATHER EFFECTS
Conifers	Positive	Slight
Broadleaf		
Evergreen		
Tropic	Negative	Minimal
Temperate	Positive	Nominal
Mediterranean	Positive	Moderate
Deciduous		
Temperate	Negative	Nominal
Tropic	Negative	Slight
Grasses and Herbs	Mixed	Moderate
Lichens	Positive	Maximum

on the average foliage moisture content of the tree or shrub canopy as a whole. All foliage of deciduous broadleaf species, on the other hand, is of the current year's growth and, with possibly few exceptions, may never reach a significant degree of flammability during its life tenure.

Growing seasons in boreal and temperate regions vary widely in their beginning and ending dates with latitude which affects both length of day and seasonal temperatures. They also differ between years in any given locality depending on the seasonal temperature, characteristics of a particular year, and in many instances upon the availability of soil moisture essential for plant growth. Some vegetation classes grow, for example, during the dry part of the year in regions of ample annual precipitation, others in the wettest portion of the year, and still others in either. In mediterranean and arid climates with marginal annual precipitation, many broadleaf evergreen tree and shrub species can survive severe moisture deficits during the predominately dry growing season and resume growth activity for short periods after even a light rain. Regardless of the nature of the growing season, all the higher plants of boreal and temperate regions go through an annual period of rest or dormancy.

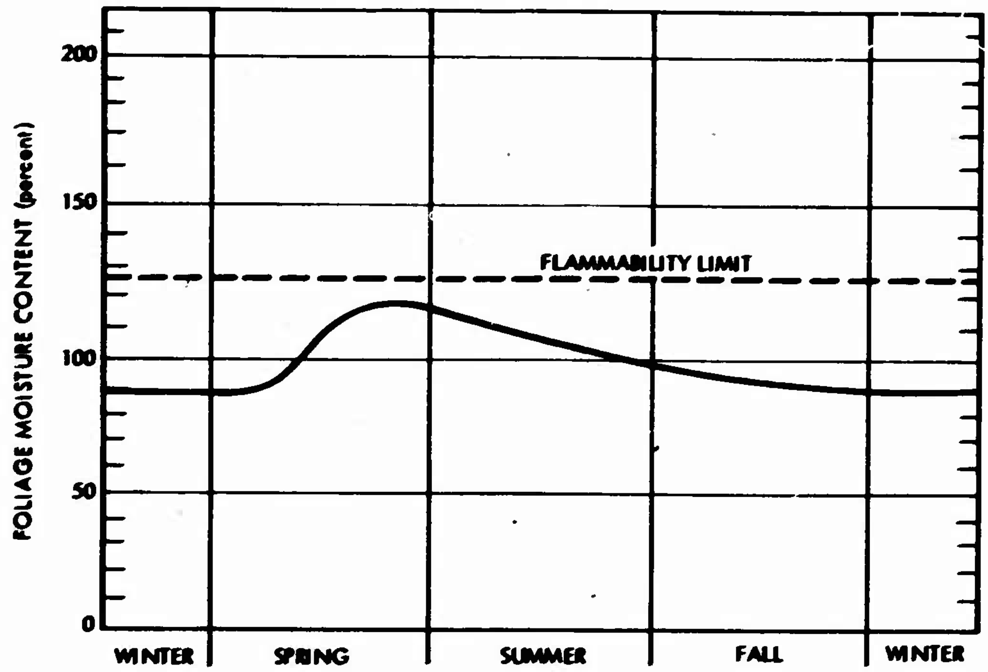

Figure 8-5. Seasonal foliage moisture content trends in interior conifer forests.

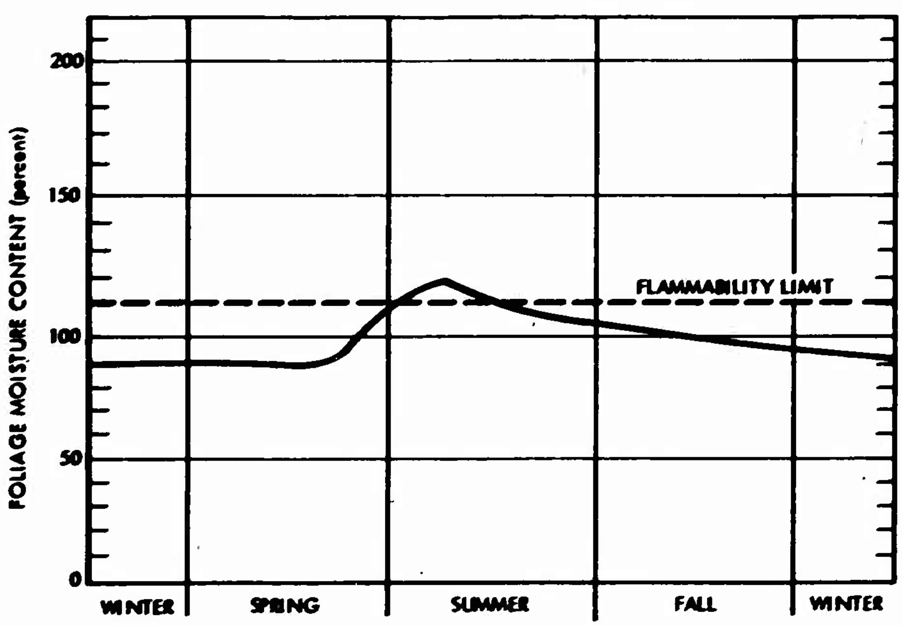

Figure 8-6. Seasonal moisture content trends in evergreens, broadleaf trees, and shrub foliage of temperate regions.

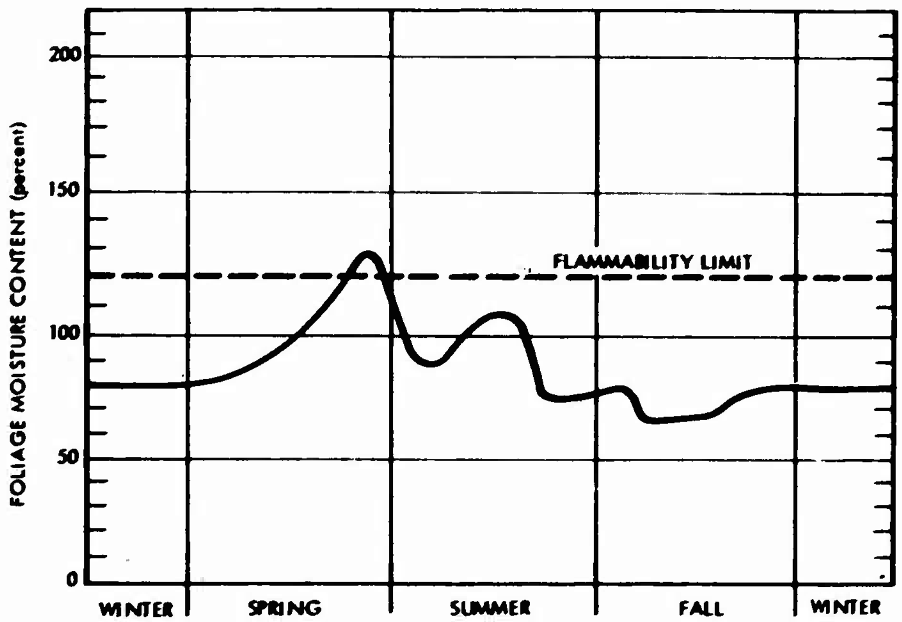

Figure 8-7. Seasonal moisture content trends in broadleaf tree and shrub foliage of Mediterranean and arid regions.

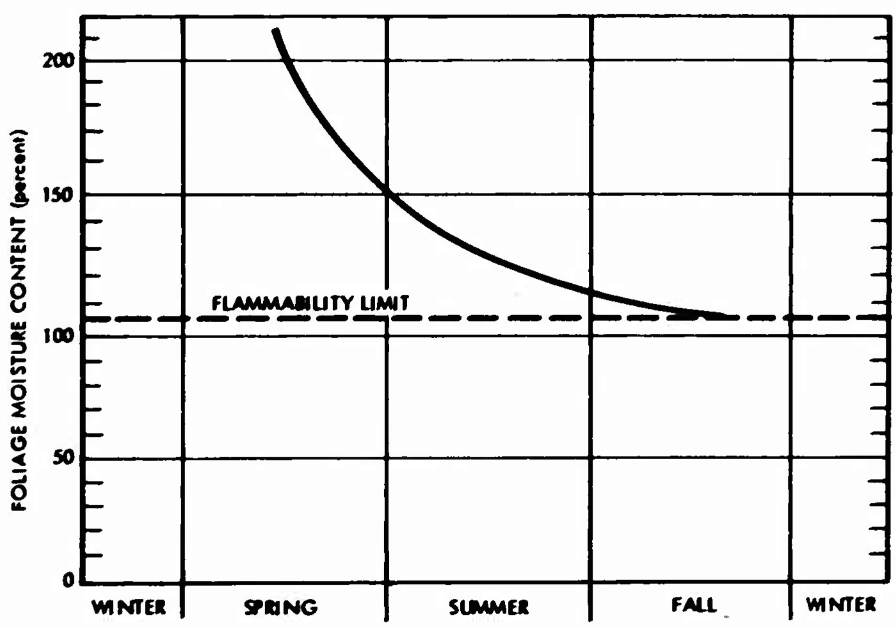

Figure 8-8. Seasonal moisture content trends in broadleaf deciduous tree and shrub foliage in temperate regions.

The foliage of conifers as a class is virtually always flammable adding to the total heat output of a fire that crowns. All conifer needles and scales have a high volatile oil content. Because of the hundreds of species involved in the world distribution of conifers, there is, of course, wide adaptation among them to weather and climatic regimes. But, whether growing in a moist or dry growing season, foliage moisture trends commonly assume a more or less typical pattern. A principal reason for this is the persistence of coniferous foliage for periods up to a maximum of at least 7 years. While this old growth foliage moisture may increase somewhat early in the growing season, it far outweighs the high moisture contents of new foliage which may only form a small part of the whole (Reference 7). The major exceptions to these normal trends appear in temperate coastal evergreen forests which do not appear to follow any particular pattern, and to the various species of larch in the northern hemisphere. These latter are one of very few deciduous conifers. In these there is a period of 4 to 6 weeks of lush growth of high moisture content in the spring, followed by a summer period of relatively high flammability.

Broadleaf evergreen tree and shrub foliage of temperate moist regions usually follow about the same seasonal trends as the conifers. The number of tree species in this group are somewhat less than those of the conifers and are somewhat more restricted in their worldwide range. Probably the most flammable evergreen tree in this group is the eucalyptus, native to Australia. The evergreen shrub species equal or exceed the number of conifer species and both the evergreen tree and shrub groups are found either in association with conifers or independent of them. While usually quite flammable, both the trees and shrubs exhibit a somewhat wider range of seasonal moisture contents than the conifers because they do not retain their old leaves for so long (Reference 8). This means that tree and shrub canopies may often have relatively high early-growing season moisture contents.

Mediterranean climates of the world are characterized by a wet winter season of intermittent storms followed by long dry summers. Annual precipitation is often 20 inches or less. Much of the vegetation in these, as well as some other arid or semiarid climates of mid-temperate zones, consists of highly drought-resistant scrub trees and shrubs and the foliage moisture contents of these may fluctuate widely during the growing season in response to soil moisture availability (References 9, 10). In addition, this factor often limits timing and length of the growing season but regardless of the moisture availability most species go through a winter dormant period in spite of generally mild winter temperatures.

Broadleaf deciduous trees and shrubs grow in a discontinuous belt around the world in the midlatitudes of the northern hemisphere. They occur less frequently elsewhere. For the most part they occur in regions of summer rainfall with length and timing of the in-leaf season governed more by local temperatures than by precipitation (References 11, 12). On warm hot days of summer their foliage often visibly exhibits a lack of turgidity because of excessive transpiration. Recovery is generally rapid, however, and moisture contents mostly remain at reasonably high levels until about the time of leaf fall. Eucalypts characteristically orient their leaf edges toward the sun, thereby allowing almost full sunlight to reach the forest floor on hot midsummer days.

Vegetation classed as grasses (including herbs) occupies so many different climatic regions that there is virtually no way to typify their seasonal moisture content trends. Annual vegetation which reproduces each year by seed has its locally adapted periods of germination, growth, curing, and dying. These are all mostly shallow rooted plants and respond more quickly to surface soil moisture availability than any others. Some have winter and early spring growing seasons while others are summer growing. Perennial grasses in some regions follow a growth pattern similar to that of annuals, in others they may remain green all year round and in still others they retain some living stems and blades while the remainder cure and die. None of the grasses and herbs are flammable when growing; they are slightly flammable when curing, and very flammable when dry. Among the group above with a mixture of living and dead parts, the composite is usually combustible to a degree depending on the relative amounts of living and dead material. Half to two-thirds dead makes a reasonably flammable mixture. Perennials as a class are more deeply rooted than annuals and are correspondingly less responsive to surface soil moisture conditions.

Lichens are unique as a class in that they are living plants while still responding to wetting and drying processes typical of dead fuels (Reference 13). A lichen is a symbiotic combination of a fungus and an alga. The fungus consists of an interwoven mass of hollow thread-like filaments. Within these filaments occur single alga cells scattered along the filament or clustered in groups. The alga contains chlorophyll and manufactures food as long as it is supplied with water and sunlight. The fungus provides the water and grows on the food produced by the alga. The fungus absorbs moisture from both its anchorage and from the atmosphere. Like dead plant material, the fungus filaments are hygroscopic. During precipitation they rapidly become saturated, but when the precipitation ceases and relative humidity of the air falls below 100 percent, this free moisture quickly evaporates. The filament moisture content then follows the approximate equilibrium moisture content of the environment. The equilibrium moisture contents of lichens tend to be slightly higher than that of most common dead fuels as shown in Figure 8-1, after short periods of drying. This is due, in part at least, to the presence of the non-hygroscopic living alga cells in the total mass.

An interesting feature of this symbiotic combination is that it can withstand long periods of extreme desiccation and start growing again when moisture is added. During these prolonged dry spells the algae also may lose much of their moisture, and equilibrium moisture content then follows a general trend.

There are a number of species of lichens of significance to fire. They include the draped spanish moss of southern United States, similar mosses in both coastal and interior regions of both hemispheres, and various components of the tundra regions such as reindeer moss. Draped mosses add materially to the relatively high flammability of many boreal forests. Because of the rapid lichen reaponse to local moisture conditions, they exhibit no particular seasonal moisture content trends and may be considered highly flammable whenever the atmospheric humidity is low. Their presence on subtropical rain forest species sometimes allows fire to penetrate these normally non-flammable forests.

8.2.6 Diurnal Variations in Living Foliage Moisture

Some diurnal variations in living foliage moisture are to be expected in all living plants. These may be caused by either moisture stress resulting from transpiration or from day to day changes in the physiological changes that take place in the leaves due to changes in food manufacture and transport of manufactured food to other storage or utilization areas. These diurnal variations are not constant from one day to another nor are they large enough to have significant influences on foliage flammability.

8.2.7 Interpretation of Seasonal Foliage Moisture Content Changes

The seasonal moisture content trends shown in Figures 8-5 to 8-8 also indicate concurrent changes in relative flammability. This relationship needs some further interpretation. The evergreen species of interest all have relatively high fat contents or waxy leaf coatings with heat contents often as much as double that of associated cellulosic leaf components. These gradually build up in leaves and needles of both the current year's growth and in the older foliage during the growing season to a maximum with the approach of dormancy (Reference 14). Much of this stored fat is utilized as a food reserve during the early growing season. Thus, the indicated early season moisture contents for even old growth foliage may not represent so much an increase in the actual leaf water content as a drop in its dry weight (including solute) during this period. Similarly, the very high initial moisture contents of new foliage in both deciduous and evergreen species do not necessarily indicate a much higher water content per leaf than later in the season. The apparent decrease in moisture is due, at least in part, to the increase in size and bulk density of the leaves as the season progresses. These factors were taken into account in drawing the seasonal relative flammability curves.

8.2.8 Dead and Living Fuel Complexes

It has been shown in previous chapters that only appropriate dead tinder fuels exposed to the fireball can be ignited following a nuclear detonation. In most cases these can result in fire only if surrounded by additional dead fuels that can provide the heat buildup required for fire to spread horizontally or increase in depth, flame height, and heat output. Living fuels alone will not burn. They must have associated dead fuel in sufficient quantity and burning rates of sufficient intensity to ignite living fuel or dead material in the form of attached dead twigs, branches, or flammable bark or lichens intermingled with the living fuels to cause their ignition. It has already been established that deciduous trees and shrubs in leaf will subtract rather than add to the total heat output of a burning forest complex except, perhaps, under severe drought. Evergreen living fuels, on the other hand, may at certain times require perhaps only minimum flame contact to burst into flame and hence aid in the propagation of fire. Laboratory work is progressing toward determination of the different flammability characteristics of living and dead fuel components, but there is not yet sufficient quantitative data with respect to species differences or relative proportions of living and dead effects on forest flammability for strictly numerical applications.

The comparative seasonal cycles of living and dead fuel flammability also enter into the determination of the flammability of the total fuel complex. Mediterranean living fuel flammabilities are usually at their maximum during that part of the year when dead fuels are also highly flammable. Dead grass is usually, but not always, associated with high flammability of other dead fuels. Deciduous forests burn better when not in leat than when in leaf. Boreal forests of close grown conifers may be in a highly flammable condition when the fire-supporting dead fuels beneath are covered with snow. There are many other examples each of which must be considered in the light of their respective climatic and seasonal weather regimes.

8.3 FIRE WEATHER DETERMINANTS

Regional climatology defines such things as length of day as well as diverse average occurrences of seasonal weather phenomena, but for field applications to time and place, cumulative and current weather elements must be measured and interpreted (Reference 15). Although the same elements are involved, fire weather is concerned more with short time trends and their interpretations than in their average behavior.

8.3.1 Ease of Ignition

The ease of ignition of tinder fuels and the flammability of the adjacent dead materials is governed, to a major extent, by the following:

1. No snow on the ground:
2. Deciduous vegetation bare or in leaf.
3. Grass—green, curing, or dead.
4. Continuous record of daily precipitation.
5. Current clouds or fog.
6. Daily maximum temperature.
7. Daily minimum relative humidity.
8. Diurnal cycles of temperature and relative humidity.
9. Current visibility, primarily for estimating nuclear thermal transmitivity discussed elsewhere.
10. Stage of growth of evergreens.

11. Quantity of fuel on the ground, and its continuity.

8.3.2 Fire Spread

The above factors are basic to determination of the ignition and combustion characteristics of dead fuels. In addition to these passive factors, others which provide the driving force needed for major fire spread are:

1. Windspeed.

2. Atmospheric in stability.

See Chapter 9 for fire spread prediction guidelines.

Note that in the above combined list there are required observations of vegetation conditions which are weather-related but which are not at the present state-of-the-art determinable from weather observations alone. For example, whether deciduous species are bare or in leaf determines whether surface fuels are exposed to the drying effects of sun and wind or shether they are protected. Grass in a tinder fuel when dead, nonflammable when green, and may be slightly flammable during the curing stage. The stage of growth of evergreens in many cases determines the extent to which they may contribute to or detract from the total forest flammability.

The need for most of these observations lies in the absence of practical methods by which living or dead fuel moistures in a forest complex can be measured directly. Regional and National Fire Danger Rating Systems (References 16, 17, 18, 19, 20) integrate these measures into relative degrees of fire severity for appropriate fuel types. These will not be replicated here.

8.4 FIRE WEATHER PREDICTION

Fire weather predicting is not, as yet, an exact science; yet with modern and improving climatological and meteorological methods approximations can be made in most areas with much more certainty than by empirical methods alone.

8.4.1 Long Range and Cyclic Predictions

For long range planning the only recourse is analysis of synoptic upper air and surface climatic records and charts of the various weather factors of direct impact on forest flammability. Admittedly such records are sparse in many regions, but in general it is possible to establish, from the available records, frequency patterns of important combinations of weather factors. From these it is further possible to calculate the probabilities of occurrence of periods when fires are likely to be ignited and spread (Reference 21).

In basing estimates on climatic data, it is desirable to have as a minimum, monthly averages of weather factors by years in order to establish not only potential fire seasons, but also differences between years and seasons and thus permit determination of likely errors of estimate of calculated probability.

Even more valuable than monthly averages is an analysis of past daily weather records for fire-prone months from which the climatic data are compiled. This more specifically defines how flammability conditions may vary within months. For example, if climatic data indicate five rainy days in a month, only daily weather records can show how they are distributed. They may vary as evenly spaced, randomly spaced, or tend to occur in one or more periods of successive days of rain. These all affect the wetting and drying regimes to be expected.

Climatic analyses of the types indicated above should be made for all world vegetation and climatic regions of potential interest. These will quickly indicate regions in which fires will not spread at any time even if ignited, regions safe from fire except in individual drought years or periods of drought years, and those regions that are regularly susceptible to fire for all or part of any year.

8.4.2 Short-Term Predictions

For short-term fire-weather predictions in areas of operational interest in regions susceptible to fire, detailed climatic analyses will also add a great deal to the background necessary for the best possible forecasting service. This latter service is necessary not only for an adequate evaluation of current fire potentials, but also for those of the immediate future, including 24-to 36-hour forecasts and 5-day or longer outlooks and attendant probabilities. Many intuitive predictions, based on real-world experience, are credible when produced by practiced woodsmen. Greater reliability is achieved when much rule-of-thumb determinations are reinforced by limited local observations such as relative humidity, wind speed, or a drought index. The discussion that follows is at a high level of sophistication, and field decisions often cannot await such text-book excellence.

In these applications it must be recognized that climatic data are generalized over quite broad regions and periods of years and that any one local area of concern in any year or season may deviate considerably from these averages. Evaluation of current burning conditions must therefore be based on local quantitative observations of the weather elements necessary to define ignitability and flammability of a given fuel complex. The minimum requirements for this purpose are for continuous daily records of visual observations of stage of growth of vegetation and instrumental measurements of precipitation, temperature and relative humidity for ignition and flammability estimates plus visibility estimates discussed previously.

Vegetation growth records for coniferous and broadleaf vegetation should show by date:

1. Bursting of new foliage.
2. End of new foliage production.
3. Current year's foliage full size.
4. Evergreen foliage approaching dormancy.
5. Significant leaf fall in deciduous vegetation and for grass:
   a. Green growth dominant.
   b. Beginning of yellowing.
   c. Dead.

The instrumental measurements should include daily precipitation, maximum temperature for the day, afternoon relative humidity and an afternoon visibility estimate. As an aid to the local forecaster and for use in estimating fire-spread potential, the windspeed and direction and atmospheric stability should also be recorded at consistent times of day, preferably in the afternoon hours. Windspeed can be measured within any of several varieties of anemometers, or in the absence it can be estimated according to Table 8-3. "Surface wind speed" is generally taken as a 4 minute average, measured 20 feet above open level ground.

Atmospheric stability in the absence of other observations ca be recorded in one of three classes as indicated by any of the following:

1. Stable
   a. A low level inversion indicated by a rising column of chimney smoke leveling off at a definite altitude.

Table 8-3. Beaufort table of wind velocities.

Beaufort Number	Map Symbol	Descriptive Word[a]	Velocity, Miles per Hour	Specifications for Estimating Velocities
0	o	Calm	Less than 1	Smoke rises vertically
1			1 to 3	Direction of wind shown by smoke drift but not by wind vanes
2		Light	4 to 7	Wind felt on face; leaves rustle; ordinary vane moved by wind
3		Gentle	8 to 12	Leaves and small twigs in constant motion, wind extends light flag
4		Moderate	13 to 18	Raises dust and loose paper; small branches are moved
5		Fresh	19 to 24	Small trees in leaf begin sway; crested wavelets form on inland water
6			25 to 31	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty
7		Strong	32 to 38	Whole trees in motion; inconvenience felt in walking against the wind
8			39 to 46	Breaks twigs off trees; generally impedes progress
9		Gale	47 to 54	Slight structural damage occurs (chimney pots and slate removed)
10			55 to 63	Trees uprooted; considerable structural damage occurs
11		Whole Gale	64 to 75	Rarely experienced; accompanied by widespread damage
12		Hurricane	Above 75	

Notes:
[a]Except "calm," these terms not to be used in reports of velocity.

b. An overcast of stratus clouds.

c. Hand placed on the ground in the open feels no particular warmth.

2. Neutral*

a. Chimney smoke rises in a poorly defined plume in calm air or rises only slowly as it drifts downwind in a light breeze.

b. Hand on the ground feels only slight warmth.

3. Unstable*

a. Few to numerous cumulus clouds visible.

b. Chimney smoke rises in a well developed column in calm air or exhibits considerable visual turbulence downwind in a light breeze.

c. Ground feels quite hot to the touch.

d. Presence of dust devils; clear visibility.

This document does not deal with weather forecasting per se. That is a specialized field in itself, the services to which it must be assumed the field commander has staff access. Observations and local forecasts of ignitability and flammability must, however, be interpreted in terms of the forest type or types of concern. The following guidelines are set forth for this purpose

8.4.3 General Guidelines for Estimating Forest Flammability

The major determinant of flammability is the quantity of fuel on the forest floor, but the only general indicator of forest flammability is the degree of wetness or dryness of surface litter and associated fuels, as determined by wetting and drying processes. The seasonal drying andrelative flammability of living foliage and the principle of equilibrium moisture content for dead fuels have been described in previous sections. This section will concentrate on the alternative periods of wetting and drying common to most climates during recognized fire seasons that control the moisture content of tinder and surface litter fuels.

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* Under stronger winds the difference between neutral and unstable air is not particularly significant in most fire spread situations.

Tinder fuels such as those mentioned in Chapter 6 exposed in the open will be rendered unignitable for a short time by rainfall in any measurable amount. Most will become fully saturated, at least near the surface, by rainfall of 0.05 to 0.10 inches. Their physical structure and exposure, however, will permit them to dry to fiber saturation moisture content on the first day after rain in which relative humidity falls below a value equal to one-half the maximum temperature for the day plus 25. For example, on a day with 90 degrees Fahrenheit maximum temperature the relative humidity must be below 90/2 + 25 or 70 percent. For lower temperatures the relative humidity must be correspondingly lower. Thereafter, tinder fuel moisture contents may be approximated by equating to the equilibrium moisture content as indicated in Figures 8-1 and 8-2.

Litter fuels under a tree or shrub canopy, unlike fine fuels in the open, receive only a fraction of the total rainfall and in many cases of light precipitation, none at all. Many studies of canope (References 17, 22, 23, 24) interception and precipitation throughfall to the forest floor have all shown the same linear relationship even though methodology is different. That is:

$$T = AP + B$$

where

T = throughfall to the forest floor

P = storm precipitation

A and B = constants that depend on forest type and condition.

From these various studies the following equations have been selected representative of typical mature forest and shrub types. They serve as examples only, but can be used as general guides in the absence of local data:

Coastal evergreen forest:	$T = 0.80P - 0.08$
Conifer forest:	$T = 0.85P - 0.05$
Broadleaf forest:	
In leaf	$T = 0.90P - 0.03$
Bare	$T = 0.91P - 0.02$
Evergreen shrub forest:	$T = 0.90P - 0.02$

The same studies also determined the moisture capacities of litter and duff covering the forest floor. These also vary according to forest type and depth of the litter and duff layer. Maximum moisture contents were measured varying from 200 to 300 percent, some of which at least included gravitational water still in the process of downward movement. Termination of this flow yielded somewhat lower field capacities.

For fire operational purposes it is desirable to separate the top two to four inches of undecomposed litter, the moisture content of which largely governs fire ignition and spread from the lower layers with different drying characteristics which are of primary concern to fire intensity (Reference 25). We have selected, for purposes of illustration, litter depths varying from about 4 tons per acre (2 inches deep) for shrub litter to about 10 tons per acre for the coastal evergreen type. The dry weight fuel values selected were:

Coastal evergreen forest	10 tons per acre
Conifer forest	6 tons per acre
Broadleaf forest	4 tons per acre
Evergreen shrub forest	4 tons per acre

On the assumption that these surface litter layers soon drain to field capacity, the interception studies also permitted selection of surface litter moisture field capacities for each of the sample types as follows:

Coastal evergreen forest	230 percent
Conifer forest	165 percent
Broadleaf forest	190 percent
Evergreen shrub forest	140 percent

These values may be either high or low but their magnitudes appear to be in the right order.

From the throughfall equations and the above assumed values, the throughfall required to raise surface litter to saturation, or field capacity, was computed and also the percent saturation resulting from any lesser amount of actual precipitation. The results are shown in Table 8-4.

Table 8-4. Percent saturation of surface litter fuels on the forest floor.

Precipitation	Coastal Evergreen Litter	Conifer Litter	Broadleaf Litter		Evergreen Shrub Litter
			Bare	In Leaf	
.02	0	0	1	0	0
.04	0	0	2	1	2
.06	0	0	3	2	4
.10	1	4	8	7	9
.20	5	13	17	17	20
.30	11	21	27	27	31
.40	16	30	38	38	43
.50	21	39	49	49	54
.60	27	47	59	59	65
.70	32	56	70	70	76
.80	37	65	80	80	88
.90	43	73	90	90	100
1.00	48	82	100	100	
1.20	59	100			
1.40	70				
1.60	80	Excess precipitation percolates downward into deep duff or soil or appears as surface run-off.			
1.80	91				
2.00	100				

If in Table 8-4 precipitation occurs on two or more days in succession, add the percentage saturation for each day of rain and add one-third the sum to the total, neglecting any values in excess of 100 percent. This addition is approximately correct because previously wetted fuels wet more rapidly than initially dry fuels (Reference 23).

At the cessation of wetting and draining to field capacity litter fuels begin to dry when the criteria for maximum temperature and minimum humidity are met as indicated above for tinder fuels. Various combinations of commonly observed temperature values between 30 degrees and 110 degrees Fahrenheit and relative humidity values from 5 percent to 70 percent established a range of minimum conditions for drying according to our drying formula. The minimum drying day unit was assigned a value of 0.3. This array strongly indicated a drying day unit of 1.0 for 80 degrees Fahrenheit and 30 percent relative humidity. The remaining values in Table 8-5 were calculated from this assumption.

The number of days required to dry the litter of each sample fuel type to fiber saturation is expressed in these drying day units. The number of units varies between types because of the volume of water stored at field capacity, the litter type and arrangement, and overstory characteristics. Required drying day units to dry litter from fuel capacity to fiber saturation for each type were established as follows:

Coastal evergreen forest	30 drying day units
Conifer forest	12 " " "
Broadleaf forest	
In leaf	9 " " "
Bare	5 " " "
Evergreen shrub forest	5 " " "

If rainfall in any case is insufficient to fully saturate the surface litter, multiply the drying day units by the percent saturation figures given in Table 8-4. To determine the actual days required for this drying, set up a daily log beginning the day after rain in which the drying day unit is recorded for that day. Accumulate these units daily and when the cumulative total reaches 30, 12, 9, or 5 for the respective sample type or a designated percentage of those days, the surface litter moisture will have reached fiber saturation.

Table 8-5. Drying day units for determining time to dry saturated surface fuels to fiber saturation.

MAXIMUM TEMPERATURE	MINIMUM RELATIVE HUMIDITY							
	5	10	20	30	40	50	60	70
110	2.1	2.0	1.7	1.4	1.1	0.9	0.6	0.3
100	2.0	1.9	1.6	1.3	1.0	0.7	0.4	0.0
90	1.9	1.7	1.4	1.1	0.9	0.6	0.3	
80	1.7	1.6	1.3	1.0	0.7	0.4	0.0	
70	1.6	1.4	1.1	0.9	0.6	0.3		
60	1.4	1.3	1.0	0.7	0.4	0.0		
50	1.3	1.1	0.9	0.6	0.3			
40	1.1	1.0	0.7	0.4	0.0			
30	1.0	0.9	0.6	0.3				

After litter fuels have been reduced to fiber saturation point, their daily fuel moistures will change in direction as indicated by the moisture equilibrium curve of Figure 8-1 as modified by the correction factors of Figure 8-2. Because of the lag in moisture content change behind relative humidity changes, the following guide is proposed:

1. Beginning on the day after saturation moisture content is reached, determine from the humidity-temperature measurements for that day the fuel moisture content equilibrium value.

2. Subtract the equilibrium moisture content value from 30 percent.

3. Subtract one-third the difference in (2) from 30 percent.

4. The result is the approximate surface litter fuel moisture content for that afternoon.

5. On each succeeding day subtract from the previous day's indicated moisture content one-third the difference between the indicated moisture content for the preceding day and today's equilibrium moisture content value.

6. If on any day the difference between yesterday's indicated moisture content and today's equilibrium moisture content is negative, add one-fourth the difference to yesterday's moisture content value to derive a value for today.

7. Start the process all over after rain causes moisture content to increase in excess of fiber saturation.

Relative humidity is, of course, changing most of the time at various rates throughout the day. The guide above applies only to afternoon moisture contents and for normal weather exhibiting regular diurnal cycles of relative humidity. Judgment alone must be relied upon for other times of day and other situations. It is also recognized that the type and density of the forest cover will influence the accuracy of estimates but here, too, if adjustments are considered desirable, they must be based on considered judgment.

Deeper layers of litter, duff, large branches, and logs change in moisture content differently than surface litter fuels in both extent and timing. Light rains affect them little, while heavy rains percolate through the surface layers and they wet deeper layers extensively. The moisture contents of these deeper and larger fuels affect primarily the quantity of available fuel for burning and fire intensity, but also to some degree rather than rate of spread.

In many regions rain falls with sufficient frequency to prevent these deeper layers or larger fuel sizes from drying significantly (for example, rainfall 3 inches to 4 inches per month). In climates with long, hot dry summers, on the other hand, cumulative drying may be severe. In areas with a generally high water table, lowering of the water level is often an excellent indicator of the extent of this drying. In areas with a deep layer of litter and duff, scraping this off to mineral soil and noting whether the soil is fresh or dry and powdery is also a good indicator of whether the lower duff layer is flammable or not. Figure 8-9 indicates heavy fuel moisture content trends at one station at 47° north latitude which has an average rainfall of about 8 inches between May 1 and November (Reference 18).

The drying of blowdown débris is a highly variable phenomenon and one that is strongly species-dependent. From what was said previously about the general flammability of coniferous foliage, the dryness of already present surface litter fuels have much more to do with resulting total flammability than the moisture content of the newly fallen material. Logging slash studies (Reference 26) have shown that the volume and distribution of the latter are perhaps much more important contributors to rate of spread and fire intensity than the amount of early drying. Branches and logs larger than about 4 inches in diameter, on the other hand, usually remain too moist to add significantly to the fire for weeks or even months after they have fallen.

Broadleaf foliage, on the other hand, must dry materially before it can add significant fuel to the forest floor. An important factor in this instance is the extent to which defoliation has taken place. Defoliated leaves lose their moisture rapidly. Those which remain attached to larger branches and stems continue to draw stored water from these sources for considerable periods of time. The drying rates in both instances depend upon how deeply the foliage is piled and the extent to which it is exposed to drying effects of sun and wind. Defoliated leaves may often dry to the flammability point within a matter of days, while that remaining attached may require a period of weeks. One exception to the flammability of larger materials occurs in the event of branch or stem breakage which exposes rotten wood. This material can add considerably to the total heat output without any additional drying.

This chapter has only indicated that wet fuels are less flammable than are dry fuels. The significance of these differences will be elaborated on in the next chapter.

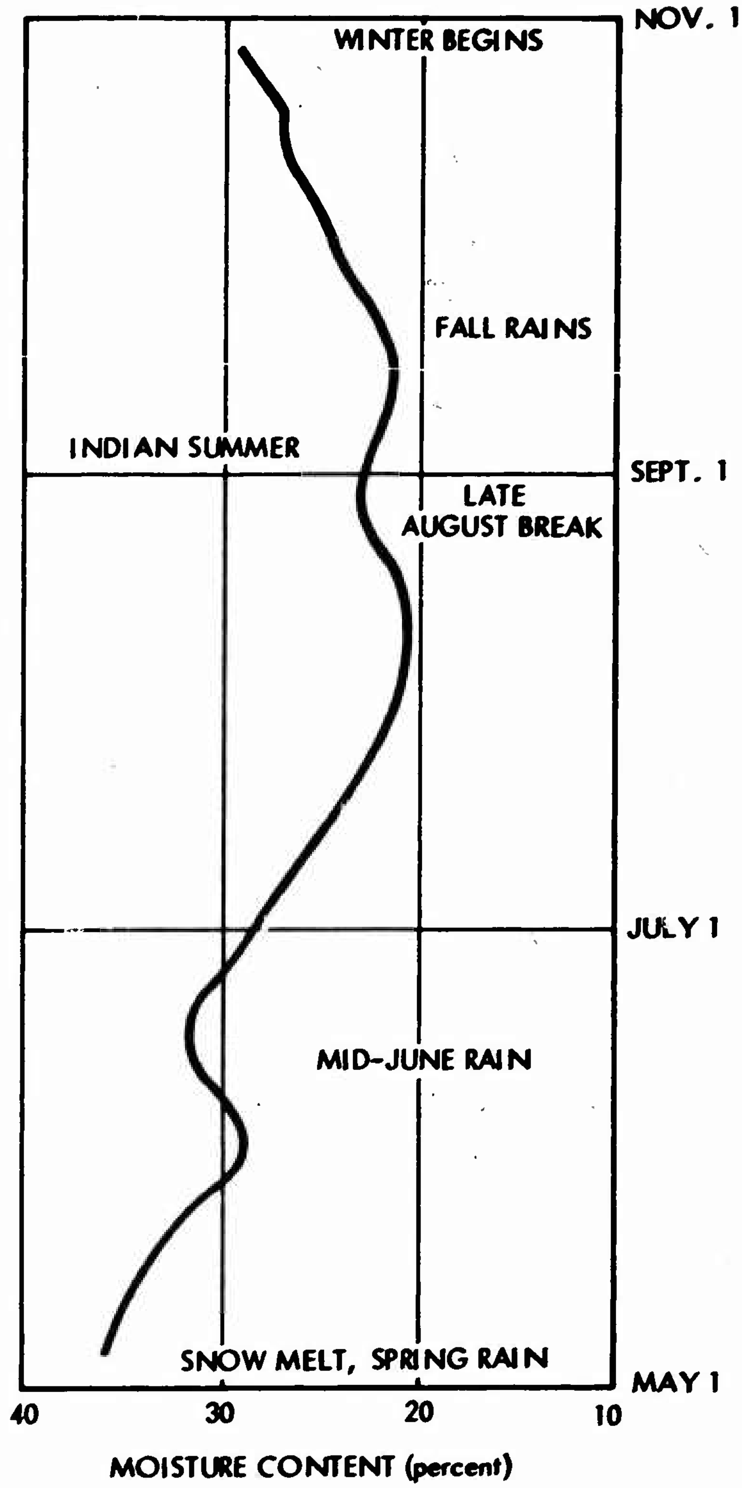

Figure 8-9. Cummulative effect of summer weather on the moisture content of heavy fuels.

8.5 MOUNTAIN WEATHER

Chapter 7 dealt with the general effects of mountain topography in establishing forest and climatic regional boundaries, the movements of air masses and the effects of altitude on vegetation zones and the like.

This section will limit discussion to a few specialized terrain effects on local fire weather often not taken into account in normal observing and forecasting practice (Reference 27). It is exclusive of alpine zones and others which, because of roughness of terrain or sparsity of vegetation, fall beyond the scope of immediate interest to nuclear forest effects.

8.5.1 Precipitation

Precipitation generally inhibits fire, and in many forest regions it occurs sporadically during periods of the year when fires are most likely to occur. Such precipitation is often the result of frontal lifting, but in mountain topography it often occurs as scattered thundershowers where the terrain is conducive to convective lifting, or it may occur as the result of orographic lifting of moist marine air by ocean-facing mountain slopes. In the latter case rainfall over extended portions of the coastline are not uncommon but they affect only the ocean-facing slopes while leaving the lee slopes and the lowlands beyond dry. Enough area is affected so that it is not usually a problem ascertaining where the rain has fallen. In the mountain thunderstorm situation the precipitation is often very spotty and areas affected can usually be determined only by visual observation at the time of occurrence or by weather radar. In either of these types of storm it is often necessary to base the amounts of precipitation received on estimate alone. How to use these estimates was outlined in 8. 4. 3.

8.5.2 Temperature

The temperatures of exposed surfaces and of air near the ground are important in mountain topography primarily because of their diurnal effects on the drying regime with variations in elevation and aspect, and because of the instability and resulting air motions it induces. Air over mountain terrain heats more by day and cools more at night than in equivalent horizontal areas of adjacent plains even though average ground and surface air temperatures are usually no higher. This large volume of warmed air results ordinarily in a small pressure differential between the plains and the mountains, with a resulting inflow toward the mountains in the daytime. This pressure differential is then reversed at night with corresponding outflow to the plains. This heating and cooling differential establishes diurnal wind flow patterns significantly influencing fire spread.

Air that is warmed by surface contact with a heating level surface during the day tends to accumulate in a thickening layer of warmed air or in mounds. These often persist until they acquire sufficient energy to overcome the inertia necessary to initiate their rise in response to buoyancy. Fire may trigger these updrafts which then augment fire convective activity and resultant fire intensity.

Air that is warmed by contact with a heated mountain slope by day soon begins to flow upward without triggering along this slope to higher altitudes. In this upward flow adiabatic cooling occurs as in the rise of free air, but is offset to a considerable degree by the continuing addition of heat as the air moves along the slope. On reaching the ridge top, this air is therefore warmer to some extent than is equivalent warm air which has risen vertically through the free air. This warm air, upon reaching the ridge top, flows off into the free air above and often to height of the condensation level where cumulus clouds are formed. This accounts for the fair weather cumulus cloud chains often observed above mountain ridges. It is particularly significant to fire spread in that fire may race to a ridge top where its convective activity virtually ceases with a corresponding decrease in fire activity.

At night these relationships change. Over the open level plain, air in contact with the surface is first cooled and continues to cool in depth during most of the night. Being cold this air is stable and remains close to the ground, contributing nothing to fire convective activity. Above the level of surface cooling in the free air, the temperature again tends to fall at the normal lapse rate. This level of maximum temperature is known as the inversion level. Fire convective activity is minimal below this level and does not extend above it.

The air lying next to mountain slopes at night begins to cool along the whole length of the slope which is radiating to the upper air and to outer space. This cooling air on the slopes,being stable and dense, begins to flow downhill following the ravines and canyons. It collects there and forms inversions, the depth of which depends on the freedom with which the cooling air can flow down these canyons and valleys and exit on to the adjacent plains. The air which flows down these cooling slopes is replaced from the upper air which gradually settles during the night over the upper peaks and ridges. In many instances this upper air will be comparatively warm and dry and thus results in a balmy night along the ridge tops with cold, damp air in the bottoms. Wind speeds and corresponding fire activity on the ridges are often greatest, too, at this time.

The aspect or direction in which a mountain slope faces is important during the day because slopes facing the sun are heated more rapidly than slopes of other aspects. Upslope air movement is thus most strongly affected by the most strong insolation, beginning with east-facing slopes in the morning and ending with west-facing slopes in the afternoon. During the early morning hours, however, east-facing slopes are being warmed from their nightime minimums while other slopes are gradually warming due to air circulation and to scattered radiation from the sky. Hence, in the north temperate zones, south to southwest slopes receive the maximum insolation and have the strongest updrafts in the early afternoon hours. Aspect is considerably less important at night than during the day because all heated surfaces cool rather quickly and reach nearly equal temperatures fairly early in the night.

These diurnal variations in both mountainous and plain topography tend to be at a maximum in the mid-latitude regions. Here too, they are frequently modified by strong pressure gradient winds or the presence of overcast which conserves both incoming and outgoing thermal radiation.

8.5.3 Relative Humidity

In the absence of precipitation, or air mass changes, the actual amount of water vapor in the atmosphere tends to remain quite conservative. Relative humidity, on the other hand, increases with decreasing atmospheric pressure at increasingly higher altitudes. This means that relative humidity, while increasing with altitude, varies at any given level almost as a direct function of air temperature, that is the higher the temperature, the lower the relative humidity. Thus we can rationalize diurnal changes in the relative humidity with proper allowance for elevation according to the interpretation of temperature changes indicated in the section above. In mountain topography the lowest 24-hour average relative humidity is often found on slopes at the elevation of the nighttime inversion. One additional aspect may be considered in the formation of dew. In both the plains and valley and canyon bottom situations, temperatures by early morning may fall below the condensation point with the deposition of dew or frost on exposed fuels. In mountain topography, however, this is a rare occurrence on the upper slopes lying near or above the inversion level.

8.5.4 Winds

Over the flatter portions of the world, pressure gradient winds resulting from the general circulation around high and low pressure areas and frontal winds associated with them tend to blow in an orderly manner with minor deviations in speed and direction modified by minor irregularities in the terrain or other features affecting the roughness of the surface over which the air passes. When these winds blow even with only moderate speeds, daytime heating of the surface contributes to thermal turbulence which makes the winds gusty and somewhat higher in speed during the early afternoon hours than at other times of day (Reference 28).

Mountain chains present the maximum degree of roughness and if high enough often block the surface winds completely or alter their directions. Also, a surface front, if strong enough to cross a mountain barrier, is often so broken up in doing so that it may be extremely difficult or impossible to identify at the surface. Often identified with mountain barriers, however, are a number of other phenomena that are of particular interest to fire weather. The most frequent of these in occurrence, consist of low gaps in the mountains and particularly river gorges which cut through them which are almost always regions of higher than average windspeed and turbulence. These are often areas of violent or erratic fire behavior and often places in which eddies generate fire whirls.

The second of these phenomena is that of the mountain wave. Moderate to strong winds blowing across high mountain ranges may cause large-scale turbulence for several miles downwind from the crest. Two associated phenomena are of particular interest to fire. One is the frequent occurrence of a large roll eddy on the lee side of the mountains causing strong upslope winds on the lee slope, accentuating fire spread rates. The second is the formation of a standing wave to leeward of the mountain ridge with strong updrafts and downdrafts extending thousands of feet in depth. These represent a highly unstable atmosphere with resulting strong surface turbulence and high intensity fires. The occurrence of this situation may frequently be detected by the occurrence of roll clouds above the large roll eddies and individual cap clouds above the overriding waves aloft.

Foehn winds represent a third phenomenon of particular interest to fire. A foehn is a dry, downslope wind characteristic of most mountain areas. Its full development requires a strong high-pressure system and a corresponding well-situated low pressure system. Mostly restricted to the cool months, two types of foehn winds are common in the temperate zones. One results from air losing its moisture through precipitation when forced across a major mountain chain. The other results from the flow of initially cold, dry air from a higher to a lower elevation. The distinctive properties common to both of these winds are that they blow downhill, are warm and become progressively more desiccating as they descend. Windspeeds of 20 miles per hour or more are often experienced in a foehn generated by moisture loss, but usually subside after a few hours. Fires burn rapidly downhill under their influence, but are short-lived.

Surface windspeeds from 40 to 60 mph are common in a foehn of stagnated airmass origin and gusts up to 90 mph have been reported. The wind often lasts for three days or longer with gradual weakening after the first day or two. They sometimes stop as suddenly as they begin. Winds from this source may affect areas two or three hundred miles in length and often as much as one hundred miles in width. Extremely low relative humidities, both day and night, high speeds and strong gusts and eddies generally characterize these winds. Fires starting under these conditions usually develop rapidly into conflagrations, often highly resistant to control with existing technology.

The pressure gradient wind systems discussed above that cross over mountain ranges affect the windward slopes and often the leeward slopes, but frequently pass over the intermediate ridges and canyons. In warm weather these interior regions are commonly affected by convective winds of thermal origin considered under the temperature discussion above. When the pressure gradient winds are light, the whole mountain system may be affected by these convective winds. And in times of strong daytime heating, the gradient winds aloft may be lifted above the entire mountain system. This commonly results from a combination of factors. The first is the general expansion of the warmed air lying over the mountain mass; second is the inflow from the plains to the mountains generated by this warming;

and third is by the upslope, upcanyon, and upvalley winds generated by the heated slopes themselves. Upslope winds generally begin one or two hours after sunrise and increase as the day progresses. But as the day wears on past noon the upcanyon winds become sufficiently strong to bend the straight upslope winds in the upcanyon direction. This results in the maximum discharge of warm air aloft over the higher peaks and ridges.

This combination of upslope and upcanyon conditions during the daytime causes fire to spread much more rapidly uphill than down during the daylight hours. One must be careful to remember, however, that these situations may be interrupted at times by the occurrence of local foehn conditions or local pressure disturbances. These daytime upslope, upcanyon winds are generally quite gusty as a result of the combination of both roughness and thermal turbulence. Convective windspeeds of 15 to 25 mph are common.

Near sundown or before as slopes go into shadow they begin to cool and a transition occurs between upslope winds of the day and downslope winds common at night. The nighttime downslope winds are stable because of their cooling temperatures and tend to flow more smoothly along the surface and as a rule at generally low speeds not exceeding 3 to 5 mph.

During the daytime the smaller draws and ravines on the upper slopes become hotter than the slopes themselves. For this reason they become natural chimneys for higher speed upslope winds or upcanyon winds and when fire occurs it tends to burn more rapidly and more intensely in these same natural chimneys. At night, gravity causes the cooling air from the slopes to immediately enter the minor drainages and concentrate in them on its downward path. The relatively low speed, however, has little effect on fire other than to materially slow down rate of spread in the upslope direction.

As mentioned earlier, the gradient winds lifted above the highest ridges during the day, may settle back down over the upper slopes at night frequently warm, steady, and of a speed determined by the prevailing pressure gradients. Fires often burn briskly along the upper slopes throughout the night when this situation occurs.

8.5.5 General

Mountain weather, as revealed in this section has many as yet poorly understood ramifications and is always subject to rapid and unforeseeable changes. A vast area of atmospheric research is yet needed to upgrade the level of mountain meteorological science. Existing models of mountain meteorological behavior too often fail to explain observed weather phenomena in this area.

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CHAPTER 9

FIRE BEHAVIOR

9.1 INTRODUCTION

The behavior of nuclear-started forest fires is best interpreted for operational purposes in a number of ways depending on the nature and distribution of ignition points and on the type of fire generated. Three situations considered with respect to ignition are: a single ignition point, multiple ignition points, and mass ignition. Each results in a completely different fire problem situation.

9.1.1 Single Fire

In the event of a single fire the most significant military aspect is its speed of advance in the direction of fastest travel. This measure is an indicator of the time required for an advancing fire front to envelop an area or to cut lines of communication, including routes of ground transit.

9.1.2 Multiple Fires

In the event of multiple fires either of two situations may prevail. The starts are far enough apart to prevent any interactions, are separated by natural barriers, irregularities in terrain or, in certain cases, by special changes in vegetation characteristics. Organized fire suppression action today, also prevents merging of many fire starts that historically (Reference 1) would have joined to become conflagrations. Each of these fires may act as an independent single fire and each will be judged as described in the paragraph above. If, on the other hand, multiple fires occur under conditions of high flammability in sufficient density and with sufficient uniformity in vegetation and terrain, they may interact, pull together and burn out a specified area. In this case the behavior is best described in terms of the time required for the specified area to burn.

9.1.3 Mass Ignition

Several vegetation types, such as exposed organic soil, many of the grasses, and lichens and mosses typical of the tundra of the far northern regions may ignite simultaneously over extensive areas. The immediate problem in this case is not so much that of spread to adjacent ignitable fuel as it is to the combustion rate in terms of Btu ft^{-2} sec^{-1} and burnout time of the simultaneously ignited area.

Further differentiation in spread characteristics is made according to the type of fire generated by the ignition. This is usually determined by the vegetation or fuel type involved. Again three fire spread types are recognized.

9.1.4 Ground Fire

Ground fires burn at and below the surface mantle in relatively pure highly decomposed organic material which may occur in relatively pure states as in peat or in various mixtures with mineral soil. They spread slowly and to a depth both of which are controlled entirely by moisture content. In periods of drought, they burn to the depth of the mineral soil or to the water table. In wet periods these soils are mostly inundated. Where such soils are covered with forests it is common for the fires to burn out only the soil. This kills the roots and eventually affects the overall flammability and since it leaves no support for the trees, it can cause them to fall without ever igniting. The burning of ground fires is always by glowing or smoldering combustion.

9.1.5 Surface Fire

Surface fires spread with flame in dead litter, twigs, branches and logs, grass, weeds, brush, surface lichens and mosses. Surface fires are primarily dependent upon dead or desiccated fuel although they may involve varying proportions of living vegetation. Among these are many upright and prostrate or semiprostrate shrubs, from a few inches to several feet high and intimately intermixed with dead surface materials. Fires in logging slash and forest blowdown debris also fall in this category.

9.1.6 Crown Fire

Crown fires are usually initiated and supported by surface fires, and burn through the living canopies of trees. If a stand of trees overtops a stand of shrubs, fire may burn crowns in the shrub cover without

without involving the overstory tree crowns, although more commonly both crowns will burn. Foliage that is killed or even consumed by a surface fire without adding to the total heat output of the fire is not considered to be a crown fire. "Crowning-out" is a common related term usually referring to an individual or small group of tree canopies that burn in the absence of continuous propagation of the flame front as a crown fire.

9.1.7 General

Any combination of the above can result from the detonation of a single large nuclear weapon.

9.2 PERSISTENT IGNITION

Fires that start and spread as a result of nuclear thermal radiation as described above, all originate from a persistent ignition source or multiple sources in tinder fuels. Such sources must be capable of maintaining effective combustion in the form of flaming, glowing, or charring through the duration of the positive phase of the blast. Whether combustion of an ignited tinder fuel persists depends on:

1. Moisture content of the tinder and surrounding fuel.
2. Fineness and other characteristics of the ignited tinder fuel.
3. Mode of ignition - whether flaming, glowing or charring.
4. Burning time between ignition and arrival of the blast wave.
5. Peak overpressure.
6. Protection of the ignited fuel from blast wave winds.
7. The ignited fuel remains in place or is moved by the blast wave.

In the natural environment some of these parameters can be calculated or estimated while others cannot. In such an environment, however, it is assumed that tinder fuels exposed to the fireball occur with random distributions, orientations and locations with the respect to protection from blast wave winds. Protection may often be caused by irregularities in the surface configuration of the fuel and of the terrain. In many fuel situations it can thus be expected that while some potential ignitions would be extinguished, significant number of ignitions will persist up to the limit of critical energy delivered to the tinder fuels involved. For airbursts of larger weapons these distances may considerably exceed airblast effects. As indicated in the previous chapter, ignited fuels close to the detonation that are broken loose and translated by the shock front or by its following high windspeeds are more likely to survive than those anchored in place.

Not all persistent firebrands will result in spreading fire. In order that spread be initiated in other fuels, the firebrand must either be in contact with, or in close proximity with, the ignitable fuels in which fire can spread. Smoldering and glowing firebrands usually require direct contact, while flaming brands must be within flame distance. Regardless of the size or burning time of the firebrand, it will not result in spreading fire if it does not meet these criteria. A second prerequisite is that the burning time of the firebrand be of sufficient length to ignite and bring about spreading combustion in adjacent fuels.

This last prerequisite may often be critically limiting to immediate fire spread. A flaming firebrand, finding itself among dead fuels too damp to carry fire at the time, is most likely to burn out before the next drying regime. A glowing or smoldering firebrand, on the other hand, must be large enough to persist for hours or even days under similar conditions before surface spread can occur. A firebrand covered with green broadleaf tree foliage resulting from blast defoliation may often persist for days until the green leaves are dry enough to burn. This was noted particularly in the 1963 Australian blowdown high explosive tests.

9.3 INITIAL FIRE GROWTH

The initiation of surface fire spread from an individual ignition point requires some minimum residence time to become established before the normal processes leading to significant spread begin to operate. This might be termed the period of initial heat buildup. This period is one of progressive fuel involvement in both vertical depth and horizontal dimension. The buildup persists until a sufficient rate of heat output is achieved that it can react with the forces causing fire to spread. In the absence of wind or slope the period usually persists as a circular fire until the central portion is burned out and the burning area becomes doughnut shaped as illustrated in Figure 9-1.

As noted in the figure the flames adjacent to unburned fuel become more or less vertical in the second stage and result in more effective heat transfer and somewhat more rapid flame propagation in the horizontal direction. Additional vertical involvement may or may not take

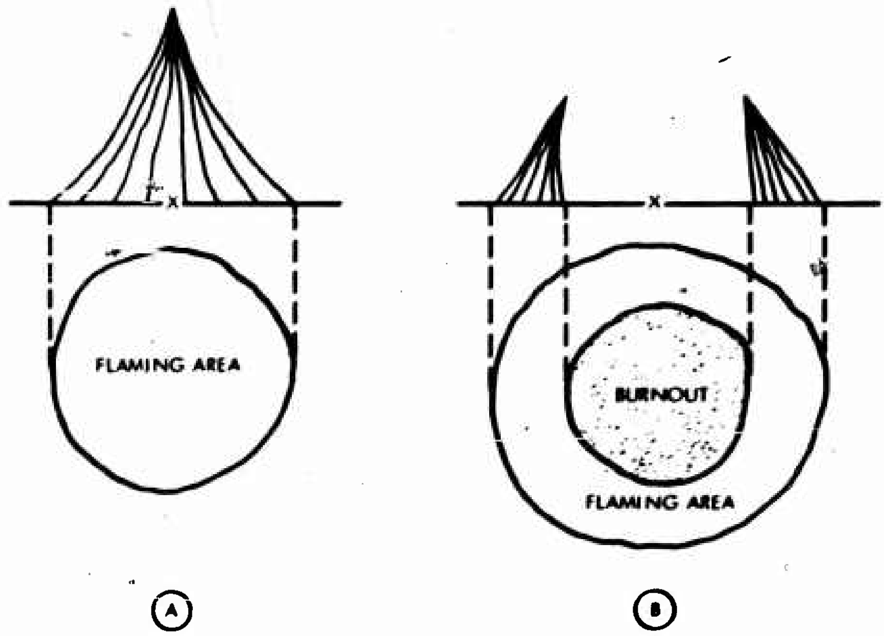

Figure 9-1. A starting fire soon after establishment begins to lean upslope or with the wing (A). After center burnout the rear of the fire retreats slowly against the wind while the front begins to run with the wind (B). Downdrafts develop in 15 to 20 minutes, often causing erratic spread.

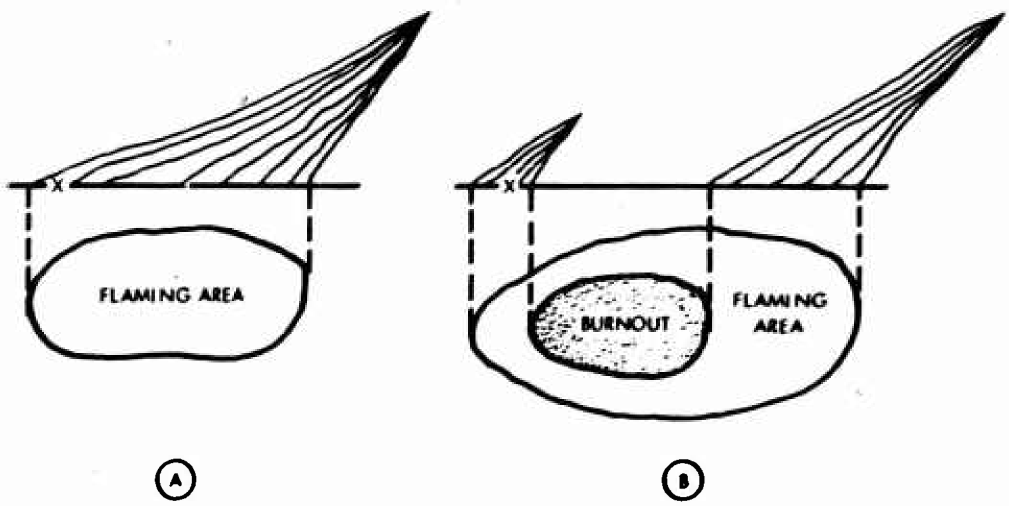

Figure 9-2. A starting fire soon after establishment begins to lean upslope or with the wind (A). After center burnout the rear of the fire retreats slowly against the wind while the front begins to run with the wind (B).

place during this stage depending on the vertical continuity and flammability of the fuel system.

In the presence of slope or wind (Figure 9-2) an establishment period is also required for the fire to generate sufficient heat and convective activity to interact with either. The time period required for this is often less than that required for the no wind case in that interaction begins before the fire center has necessarily burned out.

The minimum rate of heat output required from an established fire to make it susceptible to influence by forward spreading forces is in the approximate range of 10 to 30 Btu/min (Reference 2).

9.4 PERIOD OF ACCELERATION

After ignition, a fire either increases or decreases in rate of spread and intensity with respect to time. A decelerating fire is one that reaches a low peak intensity just before its center burns out and then decreases in spread rate and intensity with time due either to surface litter moisture contents above 25 percent, or even much lower, or to lack of horizontal fuel continuite, or to increasing moisture content. These fires develop a ragged perimeter and go out under both wind and no wind conditions.

An accelerating fire increases in spread rate and intensity for various periods of time in response to a series of complex interactions (Reference 3). These are not sufficiently well understood to yet permit reasonable mathematical evaluation. The principal factors, however, leading to acceleration are:

1. Effective fuel moisture content of dead fuels less than one-fourth inch diameter and outer shells of larger materials.
2. Kinds, sizes, and distributions of surface fuels.
3. Moisture content gradient in large dead fuels or in depth of litter fuels.
4. Fuel weights in tons per acre.
5. Surface windspeed.
6. Slope - positive or negative.
7. Burnout time of the fuel.
8. Convection column - does or does not form.

The effects which these factors have on fire acceleration can be described in general terms. Fires in fuels of large size and of deep litter beds accelerate over a longer period of time than those burning in fine fuels or shallow fuel beds. For every surface fuel condition there is an optimum but unknown special distribution of the fuel elements that will maximize the acceleration time. Time to steady state decreases as effective fuel moisture content decreases. Small positive moisture content gradients toward the center of large dead fuels or toward deeper litter layers cause longer acceleration times than do large gradients. This is a major contributor to the next factor. Acceleration time, as well as ultimate fire behavior, depends on the weight of available fuel. In the larger sizes of dead materials this may depend almost exclusively on the moisture content gradient within the fuel, permitting them to burn completely or only on the outside. Fire acceleration time increases with surface windspeeds at least up to some maximum speed depending upon the fuel type. Acceleration time increases with increase in degree of slope in the direction of fire spread. The effect in general is the same as that of wind but when the two operate together, the effects of slope change. Negative slopes have a neutral effect on fire acceleration. In the absence of wind or slope there is little tendency for fire rate of spread to accelerate after center burnout although the rate of its heat output may increase over a considerable period of time. Spotting due to firebrand transport is of course critical.

Acceleration time increases with the burnout time of the surface fuel which is dependent in turn on most of the factors listed above. When all of these factors and their interactions come into balance, the fire stabilizes and reaches a constant rate of spread and heat output or enters either before or after this point the next stage of fire development. Symbolic types of surface fire acceleration are shown in Figures 9-3 to 9-6. An important characteristic of this initially accelerating surface fire is that it is particularly responsive to surface windspeed and direction and to slope without any marked dependence on conditions in the atmosphere much above flame height (Reference 4, 5).

9.5 TRANSITION STAGE

The transition stage of a fire may begin at any time beyond its initial spread. It starts when heat output builds up to the point where convective activity begins to offset the near ground forces that normally regulate surface fire behavior. Three criteria must be met to cause a single fire to enter the transition stage:

1. Available fuel loading and burnout time must be such that depth of the flaming fire front is large in relation to its length.

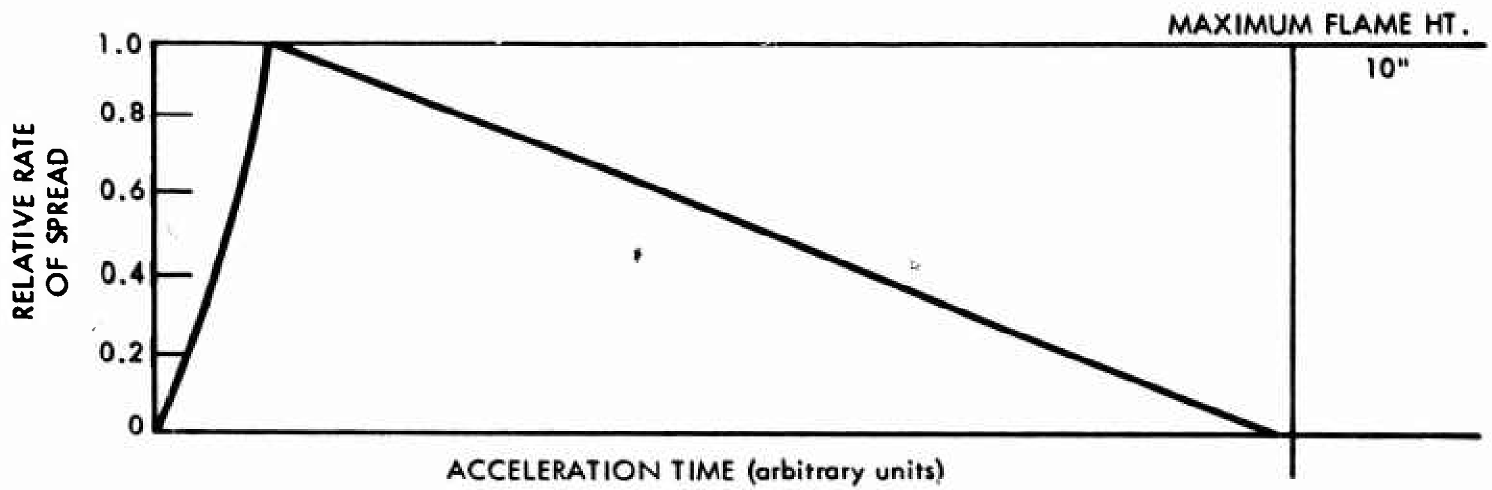

Figure 9-3. Fires in surface litter at critical moisture contents reach maximum spread rates just before central burnout, then slowly decrease to extinguishment. Maximum fuel consumption at peak is about 2 tons per acre.

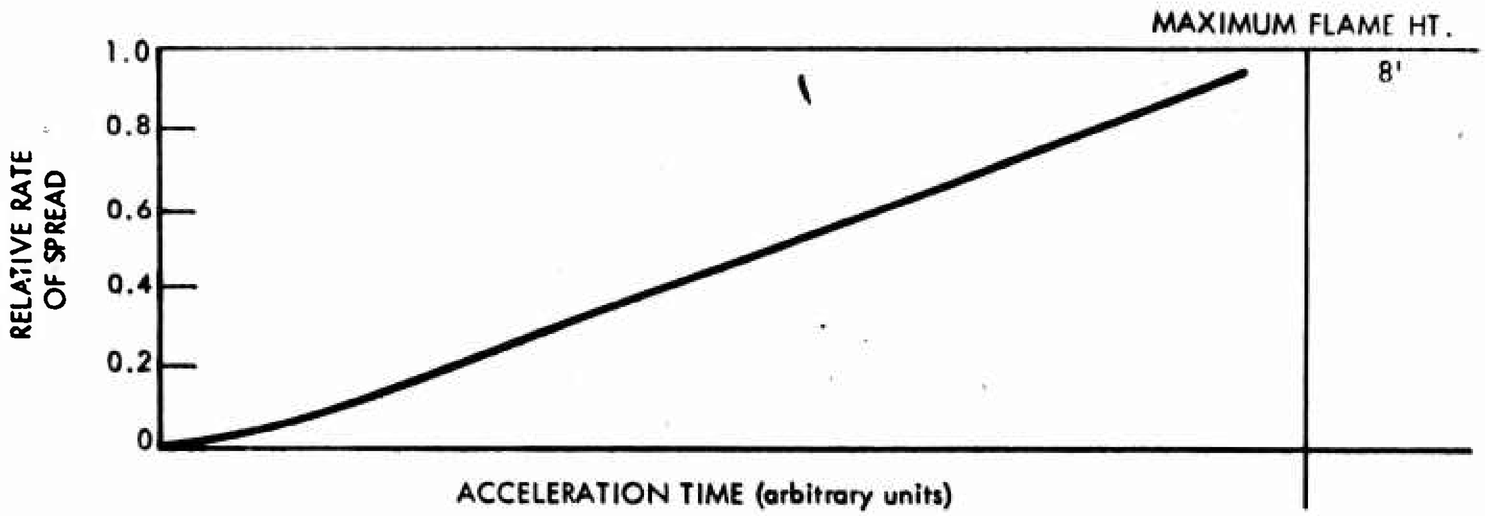

Figure 9-4. Fires in dry pine litter accelerate linearly with time in light winds. Burnable fuel about 4 tons per acre.

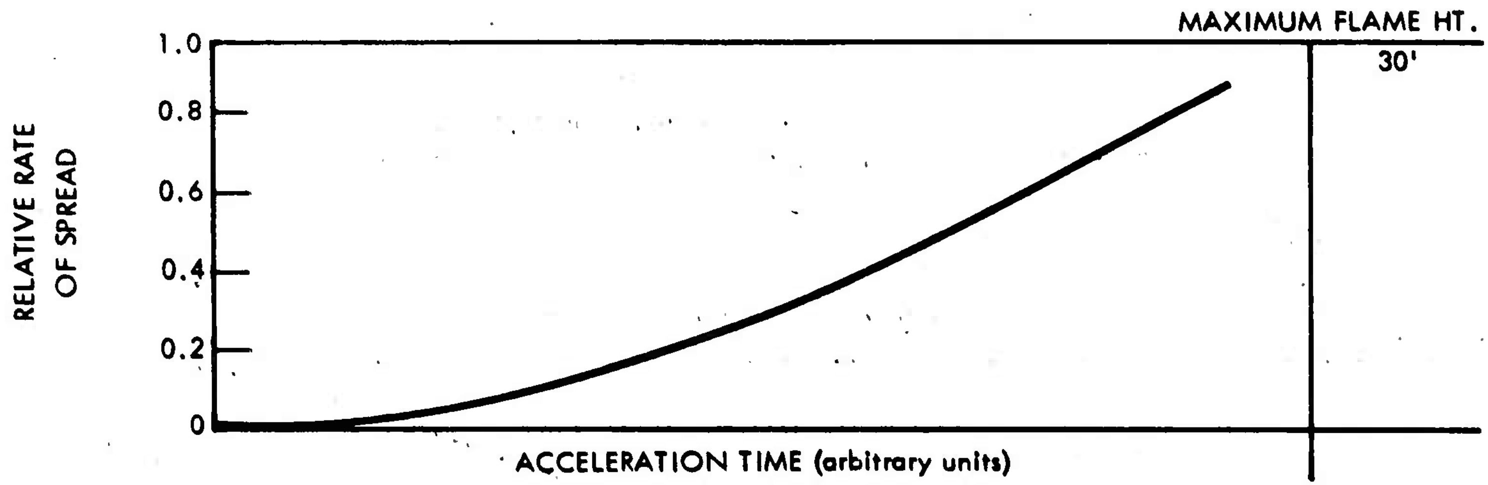

Figure 9-5. Fires in conifer slash start spreading relatively slowly while the fire is becoming established in depth. Light wind. Fuel loading about 50 tons per acre.

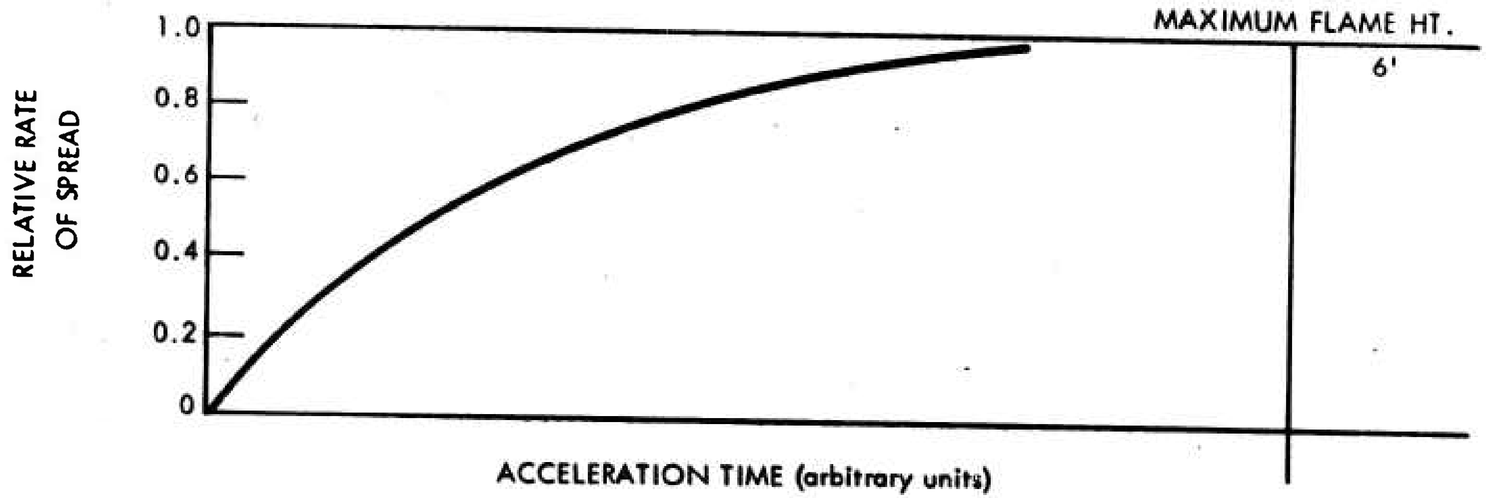

Figure 9-6. Fires in light dry grass build up rapidly because of light fuel loading and short burnout time. Light wind. Fuel loading about 2 tons per acre.

2. The flaming area must be sufficiently large that it can be considered neither a line source nor point source, but rather an area source of heat.

3. The total rate of heat output is sufficient to cause a noticeably significant perturbation in the surface wind field about the fire.

These three criteria generally rule out the probability of fires in grass, tundra, or forest litter entering the transition stage. Fires in these types may become large and assume shapes and rates of spread primarily dependent on flame reaction to surface windspeeds and directions. Leading fire edges often burn with speeds and intensities beyond human tolerance but usually present little or no difficulty to one entering the burned area within minutes after passage of the fire front. Particularly in the case of surface fire burning upslope, flow of hot combustion gasses along the surface ahead of the fire may render a considerable area uninhabitable for some distance ahead of the flame front.

Situations in which the transition stage are common involve heavy fuel loading:

1. The fire starts in a heavy fuel type such as logging slash or forest blowdown.

2. The fire burns from a light into a heavy fuel type.

3. A litter fire has become a crown fire in brush or timber types or combinations of both.

Mechanisms that may trigger the transition may be those that vary with either space or time. Those varying with space include fires which burn from a light into heavier fuel types and those which may burn from lesser slopes to steeper slopes. Those concerned with changes in time include particularly windspeed and changes in fuel moisture and temperature and especially so when accompanied by a change in stability.

In the absence of wind, initiation of the transition stage begins when the burning area and its heat output reach a point where the upward force of its convective updraft and accompanying peripheral surface inflow become the dominant factors in determining how the fire spreads. Continuing development is marked by rapid rise of the convection column as an organized structure with the absence of disorganized plumes of drift smoke at the lower levels.

A similar fire burning in wind is initially driven forward by a function of the full force of the ambient wind causing the leading edge of the flame to bend over and into unburned fuel. Byram has expressed this phenomenon in terms of flow of kinetic energy in the wind field as a function of the cube of the wind speed (Reference 1). The important thing to note here is that the function cube of the windspeed representing the total energy in the wind field as operating on the flame in a horizontal forward direction. As the depth of the flaming area and the overall fire intensity increase, the whole depth of the flame zone begins to interact with the ambient wind field. This gradually weakens the wind forward energy component through vertical entrainment and the generation of turbulence within the flame zone. The beginning of this interaction marks the beginning of the transition stage. Visible signs are a gradual increase in flame height and a more nearly vertical flame front.

The completion of the transition stage is marked by a fully developed three dimensional fire usually with a towering convection column. Here there is a combination of very strong termperature gradient and high wind shear between the flame and lower convection column and the ambient air. This causes the ambient wind to turn and flow around both sides of the fire and lower convection column forming twin eddies on the lee side just as in the flow of wind around a solid object (Reference 6). When this state is achieved, wind force which may cause the whole convection column offering resistance to this force to bend in the direction of the wind is thus expressed by the drag force, a function of the square of the wind speed.

9.6 LARGE FIRE BEHAVIOR

The rates of spread, intensities, and shapes attained by large fires can be characterized in only very general terms. No two fires are ever the same. Each is governed by a large number of interacting parameters of fuel, weather, and topography and by their interactions with the fire itself. And, each of these is constantly changing with both time and space. We can differentiate with reasonable certainty the general characteristics of large fires in light fuels from those that meet the criteria for passing through the transition stage.

The least complicated form of large fire behavior is that exhibited by fires burning in light fuels such as grass, tundra, deciduous broadleaf litter (when the trees are not in leaf) all of which at any stage of development are exposed to the surface winds. These light fuels have the greatest sensitivity to weather. Diurnal changes in fuel moisture, temperature, and windspeed greatly affect the behavior of these fires. They normally burn most aggressively during the midday hours, when the moisture decreases and windspeeds tend to increase, and quiet down when these factors are modified during the nighttime hours. Being so sensitive to weather, fires in fuels that are reasonably dry, may burn for distances of several miles within a few hours under brisk winds. Fires are also sensitive to slope, burning more readily uphill than down and if wind direction happens to be upslope, they may travel with great speeds until they reach the top of a ridge. Wind is usually dominant, however, in directing the course of these fires.

Spotting ahead of the flame front is a common daytime occurrence in these light fuels, but usually only far enough in advance of the flame front to be overrun by the main fire before they become organized. An important exception to this is in some of the woodland and scrub savanna types in which the advancing fire involves either individuals or groups of trees or shrubs. When these ignite they generate hot spots and frequently throw burning embers one-fourth mile or farther ahead of the front. These may, or may not, become difficult depending upon the spotting density.

In the absence of heavier fuels, capable of maintaining glowing or smoldering combustion throughout the nighttime hours, it is common for large portions of the perimeter of fires in these lighter fuels to go out at night.

The environments in these fast moving flame fronts and for short distances ahead of them are severe even though they may be of short duration. Even one breath of hot combustion gas ahead of the fire or within the flame zone is lethal* even though thermally hardened equipment may not be damaged. The flaming zone on the flanks of these fires, on the other hand, is often narrow enough in depth that it can be penetrated without difficulty. Numerous cases of asphysiation have been recorded in cases where personnel took refuge in road cuts over which the fire passed or in small cleared areas which the fire burned around, but surviving personnel once inside the burned out area beyond which the fire has passed, are not subject to further harm. Chances of survival appear to be related directly to the burnout time of fuel particles.

Large fires in heavy fuels are those that generate the most complex and least predictable forms of fire behavior. Under less severe burning

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* The U.S. Forest Service thoroughly investigates all fire situations leading to fire injury or fatility.

conditions represented by high fuel moisture contents, overcast skies, or strong temperature inversions, for example, fires in these fuels tend to burn in an orderly manner and remain more or less tractable as long as the weather holds. Under more severe burning conditions, any intense fire having passed through the transition stage may behave in a variety of ways depending on total thermal output, surface windspeed, complications of topography, instability and vertical wind profile as well as perhaps on other factors. In each of these, rate of spread acceleration may or may not extend beyond the transition stage. It usually does because of increased total thermal output with increasing fire size.

There are a number of commonly recognized forms of intense large fire behavior involving a moving fire front. They all usually burn in fuels with low moisture content and high total heat outputs but with different wind profiles and degrees of atmospheric stability.

In all of these cases there is generated in the flame zone an initial energy of the combustion process. In vertical or tilted convection columns this results in acceleration generated through the combination of combustion gasses and large volumes of air required for the combustion, both expanded quickly to four or more times the volume occupied at the ambient air temperature. This acceleration gives an added momentum to the convection column difficult to identify or measure on small-scale fires. It can be approximated in only very rough terms on larger fires because of the variable and unknown volumes of heated ambient air and the incompleteness of combustion.

The different forms of fire behavior of special interest are concerned with convection-wind interactions. For convenience they will be designated as types. Their order of listing reflects primarily the complexity of the various systems of interest. Their frequency of occurrence varies with fuel, topographic and atmospheric differences. (See Table 9-1.)

9.6.1 Type I. Towering Convection Column with Light Surface Wind (Figure 9-7)

This type of fire occurs with low surface windspeeds and low to moderate speeds aloft. Instability is usually present near the ground and may vary from neutrally stable to moderately stable aloft. Its towering convection column which may reach from 25,000 to 50,000 feet in the air remains vertical or nearly so above the surface and moves forward embedded in the air aloft much as does a towering cumulus cloud. Being anchored to its heat source, in this case, the convection column provides the driving

Table 9-1. Summary of wind-convection interaction types.

No.	Type	Dominant Features
I	Towering convection column with light surface winds	Moderate to rapid fire spread persistent until changes in the atmosphere or fuel
II	Towering convection column over a slope	Rapid short-term spread with convection cutoff at ridge crests
III	Strong convection column with strong surface winds	Fast, erratic spread with short-distance spotting
IV	Strong vertical convection cutoff by wind shear	Steady or erratic fire spread with occasional long-distance spotting
V	Leaning convection column with moderate surface winds	Rapid erratic spread with both short- and long-distance spotting
VI	No rising convection column under strong surface winds	Very rapid spread driven by combined fire and wind energy; frequent close spotting
VII	Strong surface winds in mountain topography	Rapid spread both up- and down-slope with frequent spotting and area ignition
VIII	Multiple head fires (mostly types I through V	Broad fire front with two or more independent convection columns

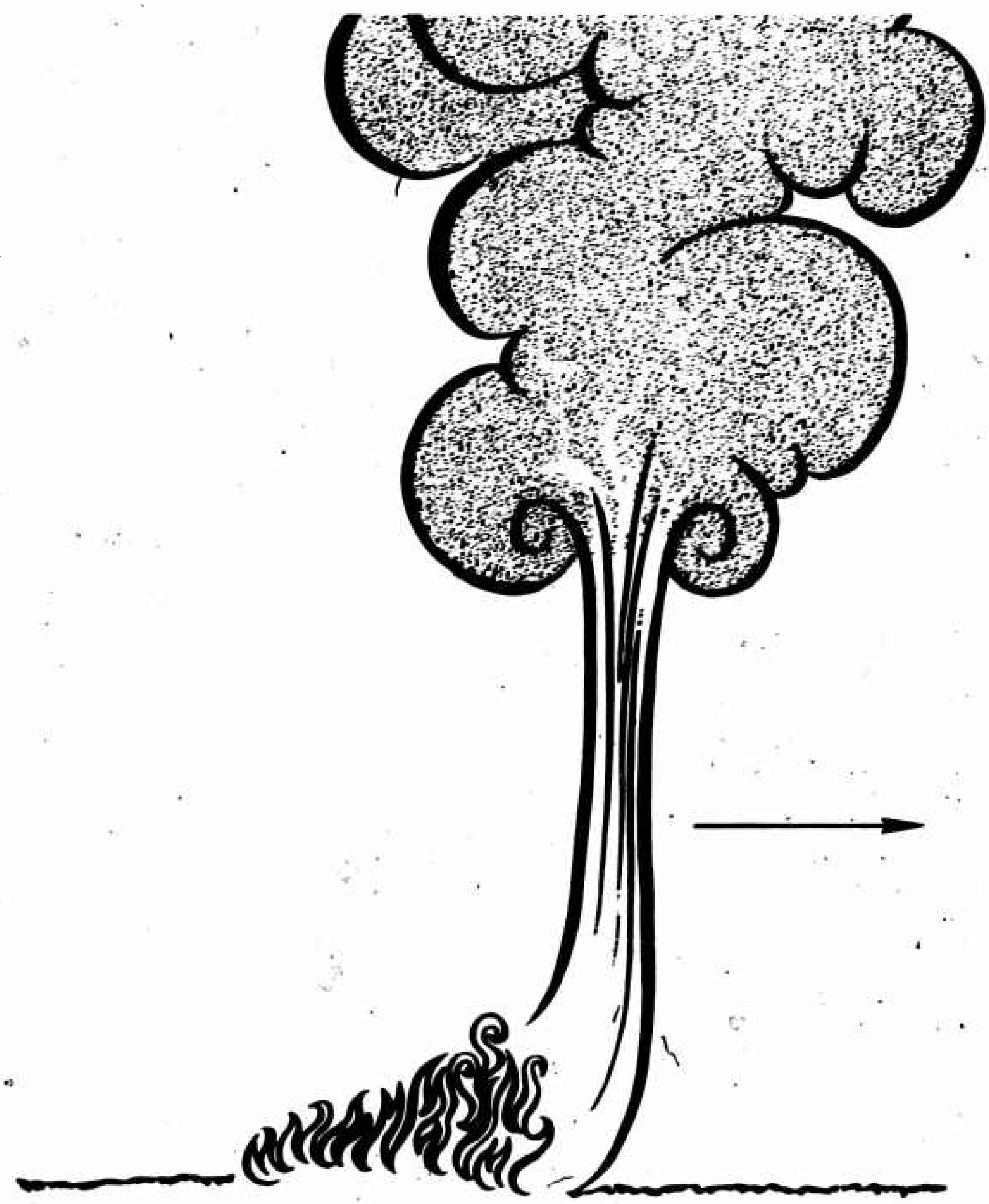

Figure 9-7. A towering convection column in gently flowing air may pull a fire in heavy fuel forward much faster than would be predicted by surface wind observations.

energy and actually pulls the fire along. The low surface windspeeds have negligible effects except to perhaps cause slight turbulence in the leading flame edge. Virtually all combustion products are carried aloft in the rapidly rising convection column so that even drift smoke is absent to negligible near the ground. For the same reason, spotting is negligible because potential firebrands are carried so far aloft that they burn out before dropping back to the ground. The spread is usually quite uniform with little tendency to fan out and the forward rate of spread depends on both the strength of the winds aloft and on the fuel loading, rate of combustion and burnout time. These fires may burn for several miles across country during the midday and afternoon hours. With increasing stability near the surface in the late afternoon and early evening hours the convection strength decreases and may cease by nightfall.

9.6.2 Type II. Towering Convection Column Over a Slope (Figure 9-8)

Fires burning under wind and stability conditions similar to those indicated for Type I, also exhibit a towering convection column tending to move with the winds aloft but with some added effects and limitations imposed by the characteristics of the slope. The convection column is still anchored to the fire heat source, but the energy providing the driving force for the fire spread derives in this case not only from the force of the convection column but also by the tilt of the slope which increases the efficiency of heat transfer from the fire to the unburned fuels beyond. The effect is to increase rate of spread. As a general rule of thumb, fire will double its spread rate on a 30 percent slope compared with flat ground. and double again on a 50 percent slope, and perhaps considerably more, depending on wind. Vorticity at the head of the fire tends to increase with slope steepness and on slopes more than 60 to 70 percent often burn explosively, but perhaps even more commonly, slow down because of ground-induced turbulence. Drift smoke is plentiful along the slope to the ridgetop where it moves off into the upper air. The fire may move up this slope in a relatively narrow band or fan out depending upon the surface drainage pattern. Small draws tend to become individual chimneys. If the slope terminates in a ridgetop with a negative downslope on the lee side, the strong convective updraft reaches a maximum at the crest, then cuts off quickly with burnout of the fuel on the windward slope. This phenomenon is sometimes accompanied by an updraft on the leeward slope tending to carry firebrands back up to the ridgetop, thus reducing spotting. When this fire run is over, continued spread is either stopped or or progresses on down the lee slope as a creeping fire. If, on the other hand, a lee wave exists on the downwind slope or the windward slope terminates in a plateau, the fire continues its progress as in Type I case. Fire whirlwinds may develop at the crest and scatter firebrands in all directions.

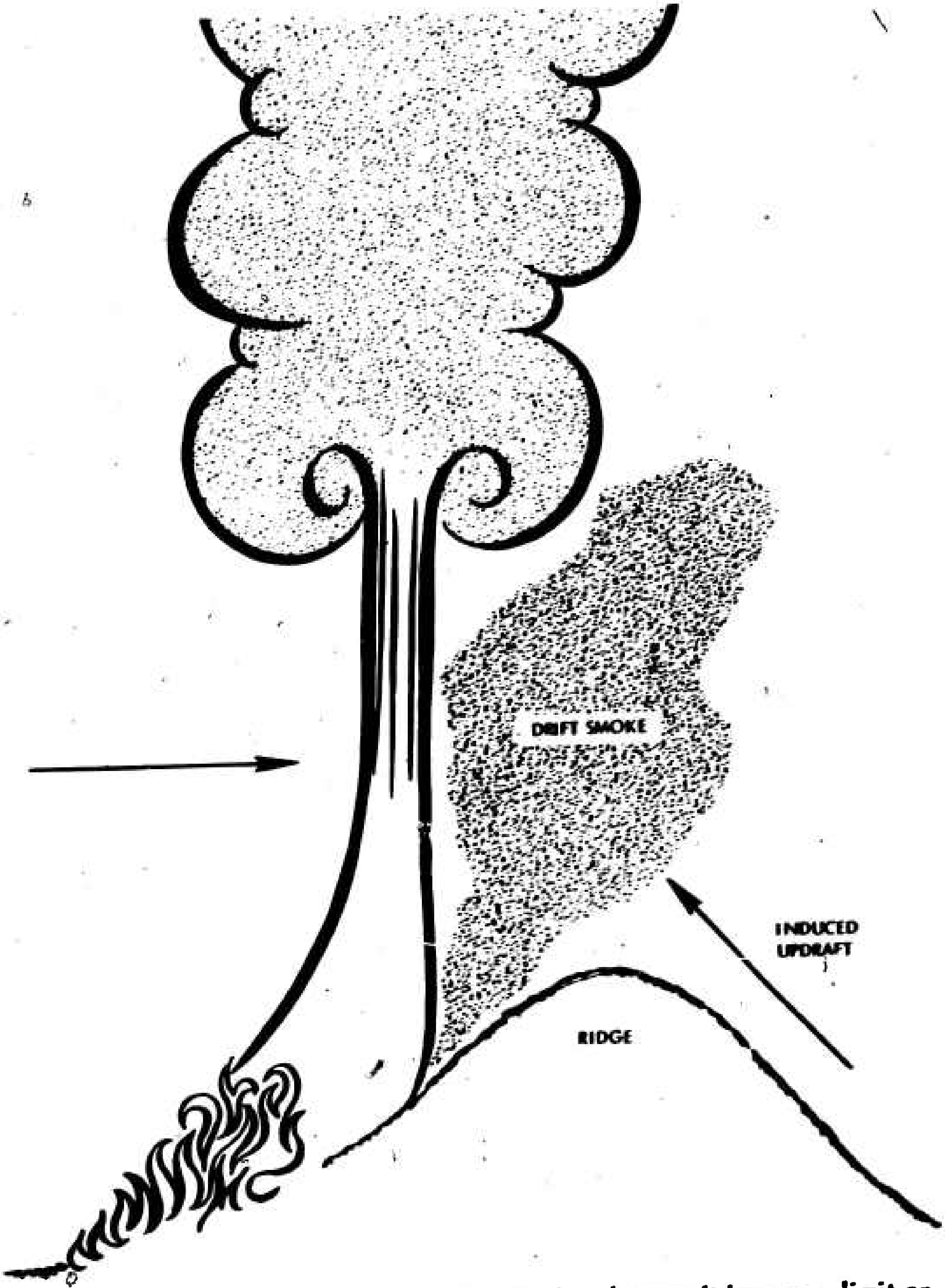

Figure 9-8. Slope multiplies uphill spread of fire but the summit imposes a limit on the convective activity.

progress as in the Type I case.

9.6.3 Type III. Towering Convection Column with Strong Surface Winds (Figure 9-9)

Fires burning under the influence of strong surface winds with decreasing winds aloft, develop a towering convection column and move forward more rapidly, but somewhat more erratically than do those under Type I. Stability near the ground is of little significance in this type of fire. The towering convection column moves forward with the winds aloft, but still being anchored to the heat source moves only as fast as the fire spreads. The driving energy for this type of fire is derived from the force of the convective activity strongly supplemented by the force generated by the strong surface winds. These winds form a convergence zone ahead of the fire with resulting strong vorticity at the head of the flame front. This lattter is very effective in spreading the fire into unburned fuels and at the same time carrying firebrands aloft which may result in considerable short distance spotting ahead of the fire. This combined activity usually causes the fire front to fan out as the fire advances. There is usually considerable, but not necessarily dense, drift smoke for considerable distances downstream. The spread rates of these fires are considerably higher on the average than those of Type I but are somewhat more variable because of frequent changes in the windspeed and often in its direction. The towering convection column usually breaks up at night but the surface windspeed may continue or decrease according to its origin. If the strong winds continue, the rate of spread at night is considerably less, but still significant and drift smoke downstream often becomes dense to make visual observation of the fire's behavior extremely difficult.

9.6.4 Type IV. Strong Vertical Convection Cutoff by Wind Shear (Figure 9-10)

Large fires often occur under conditions typical of Types I or III, but with an otherwise towering convection column sharply cut off by a discontinuity in the airflow aloft. This discontinuity is marked by a sharp change in either windspeed or direction, though usually the former. Such are common in the region of 5,000 to 10,000 feet above the surface. The surface fire behavior is little affected by this phenomenon but it does represent a highly dangerous situation with respect to long-distance spotting. Depending upon the types of fire-brands available, spot fires may occur 6 to 10 miles in advance of the fire front, and occasionally even farther. They may occur along the axis of the major fire spread or to one side or the other, depending upon the direction of the windstream aloft. These spot fires are often far enough

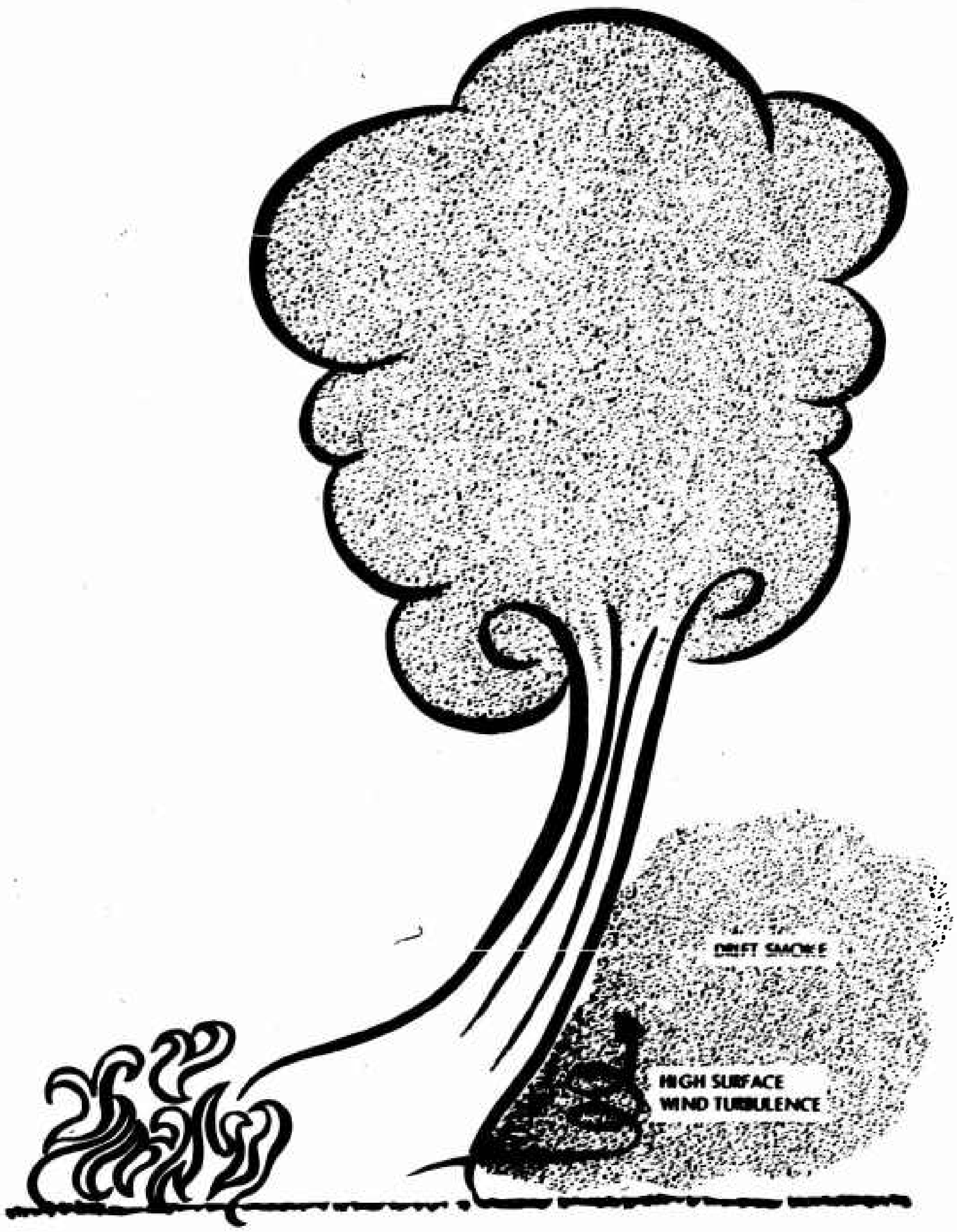

Figure 9-9. High surface winds coupled with strong convective activity increase both rate of spread and erratic fire behavior.

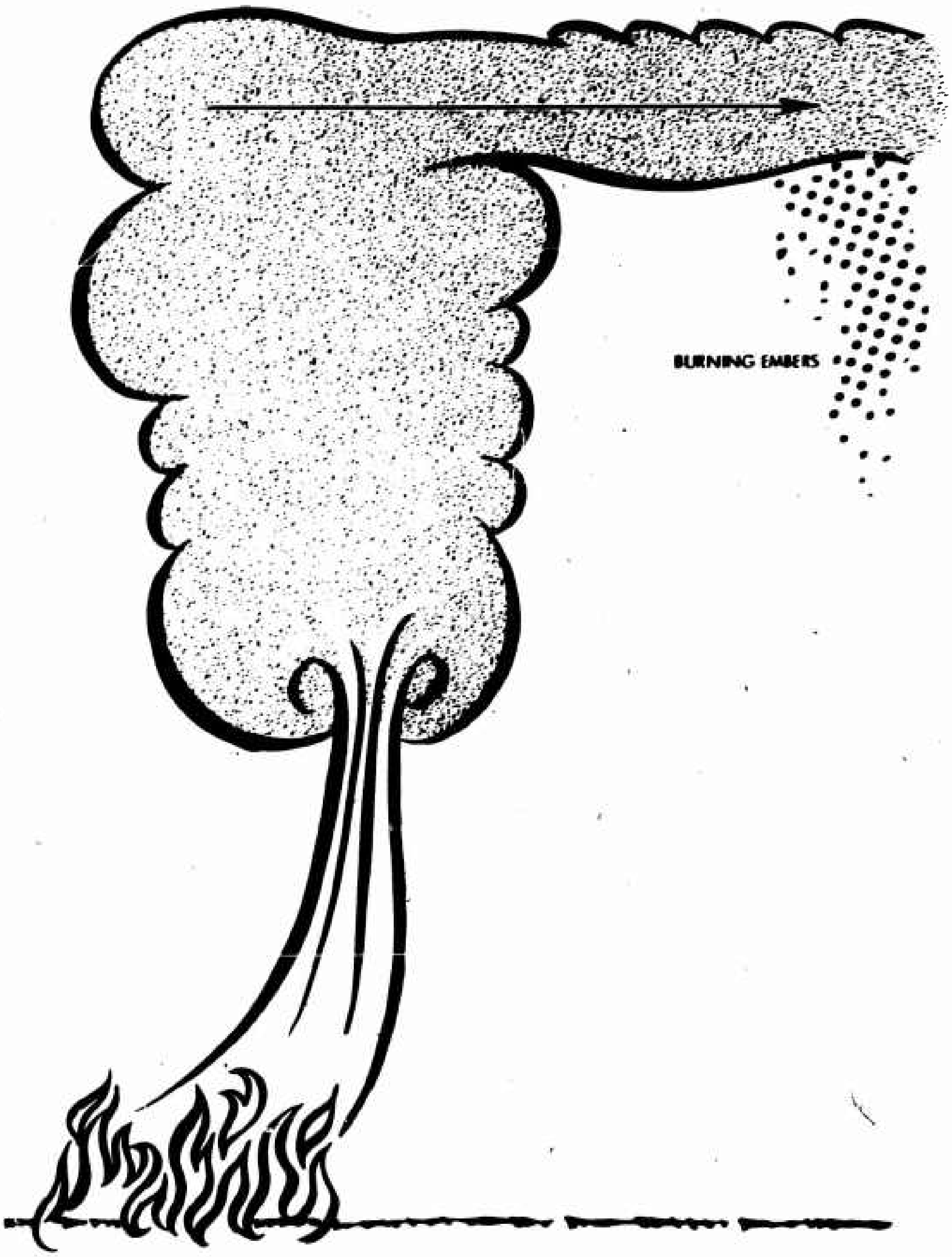

Figure 9-10. Strong wind shear aloft has no apparent effect on convective activity but does markedly increase spot fire potentials.

ahead of the main fire front that they must be considered as separate or independent fires. Recent theories also postulate a vortex corridor on each side of the convection column, carrying brands outward and downwind.

9.6.5 Type V. Leaning Convection Column with Moderate Surface Winds (Figure 9-11)

Fires occur more frequently than not in situations in which the winds aloft increase with altitude. The stronger winds aloft are usually accompanied by at least moderate surface winds. In such cases both the convective energy and the surface wind field energy join in carrying the fire forward but with increasing windspeeds aloft, the convection column bends more and more in the direction of those winds. With the increased mixing of the convection column gasses with the ambient air aloft, the column becomes quite disorganized or diffused with drift smoke carried aloft far downstream. Under these conditions there is also considerable drift smoke for appreciable distances in advance of the fire front. The surface wind acts much as that in Type III forming a convergence zone downstream with a high degree of vorticity which is often very erratic along the fire front. These fires tend to fan out or broaden as they advance and the actual fire front is often difficult to establish. The reason for this is that there is not only close-in spotting but spotting more or less continuously, but with less frequency, for varying distances downstream. In extreme cases the forward spotting distances may often approach those indicated for Type IV. The fastest spread and most violent activity is usually confined to the midday and afternoon hours. Without change in the wind field, on the other hand, rapid spread may continue far into the night.

9.6.6 Type VI. No-rising Convection Column Under Strong Surface Winds (Figure 9-12)

Fires sometimes occur in a neutrally stable to stable atmosphere and strong surface winds that prevent the convection column from rising more than a short distance above the surface. In such instances, fires are essentially wind driven. The same combustion energy responsible for initial convection acceleration in the Type I fire still remains within the system, however, and adds to the fire intensity if not to its rate of spread. Theories have been postulated, but no measurements have been made, however, of the manner in which this energy is utilized or dissipated. These fires are always fast moving with the rate of spread usually more or less constant over considerable periods of time, varying only with such changes as may take place in the windspeed. These fires are often long and narrow in shape with little tendency to spread out except as the wind may vary in direction. Drift smoke is often carried forward in a narrow ribbon for perhaps a hundred miles or more with slight dissipation. Spotting in these fires is at a minimum and except for specific fuel types (e.g., rough barked

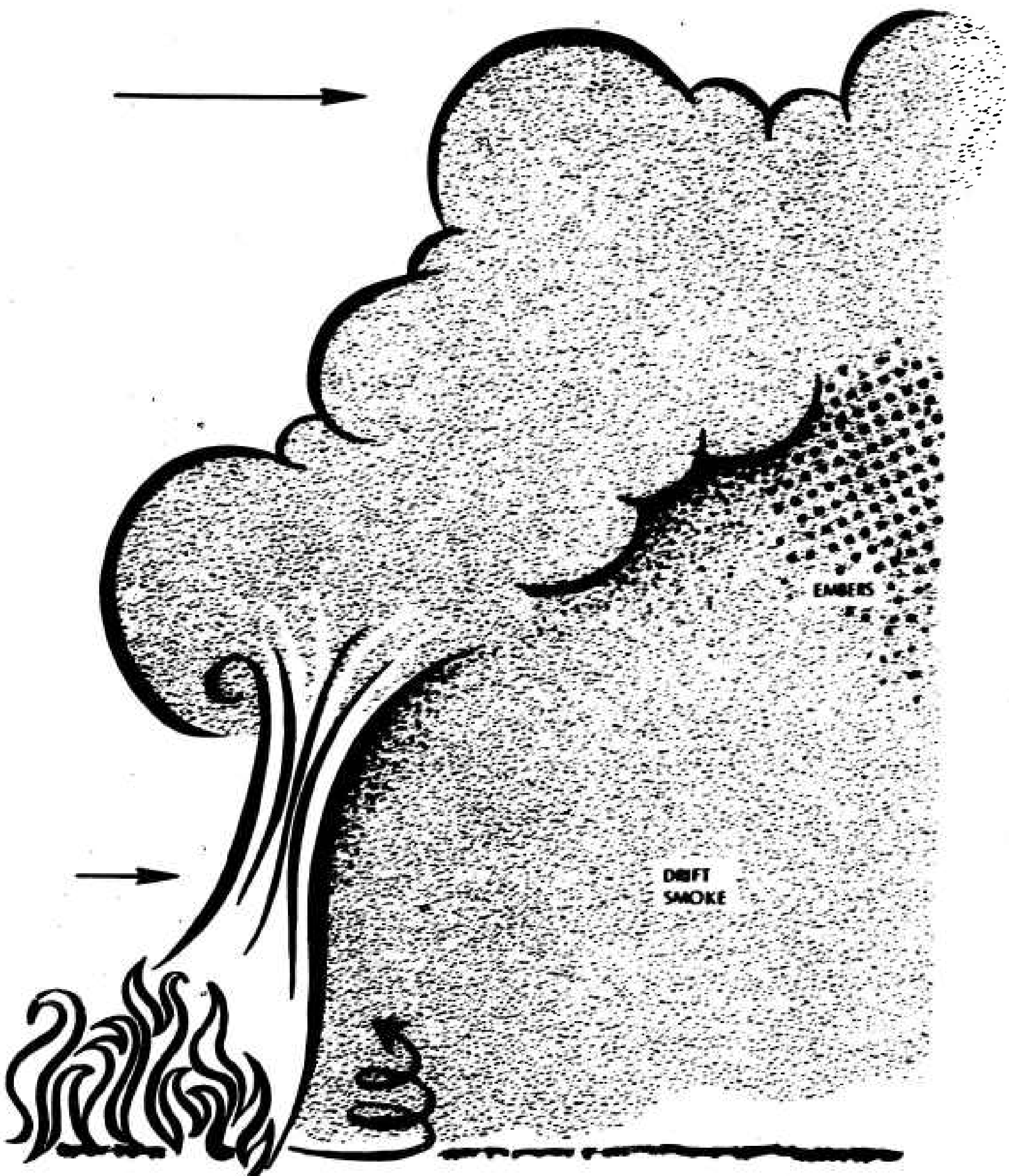

Figure 9-11. Strong winds aloft break up the columnumnar structure of the convection to form a difuse smoke mass flowing downstream. Behavior is often erratic. Spotting frequent.

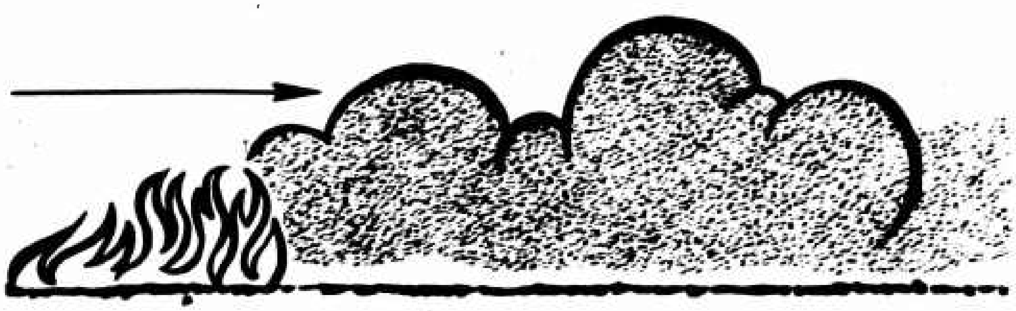

Figure 9-12. Strong surface winds often confine fire convectivity close to the ground. Spread is rapid and steady with frequent close-in spotting.

eucalypts) is confined to very short distances ahead of the fire front. If the air remains dry, these fires may run both day and night as long as the winds persist.

9.6.7 Type VII. Strong Surface Winds in Mountain Topography (Figure 9-13)

Fires burning under the conditions described for Type VI but in mountain topography spread up the windward slopes with extreme rapidity but at the same time showering the lee slope, intervening valley, and the next slope with great numbers of firebrands and resulting spot fires. This area ignition, coupled with the highly turbulent winds in these lee areas, often results in the rapid development of mass fire with extreme heat outputs and considerable convection activity above the main wind stream at the same time that the fire is burning across the next ridge. Here again it is frequently difficult to identify the main fire front and visual surveillance is often impossible because of the extreme smokiness ahead of the fire. This type of fire behavior usually persists as long as the strong winds, or until the fire runs out of fuel.

9.6.8 Type VIII. Multiple-head Fires

Any of the intense burning fires such as those described in Types I through VII always tend to break up into two or more separate head fires whenever the fire front becomes more than one or two miles long. The reasons may be one or a combination of several. Probably one of the most common causes is the atmosphere itself. Extended large fire heat sources tend to break up into separate convective cells and even within relatively short distances surface windspeeds and directions may differ sufficiently to cause these to spread in a divergent pattern. Other common causes are changes in vegetation type, changes in the terrain, or the fire front burning into barriers such as lakes, cultivated or other

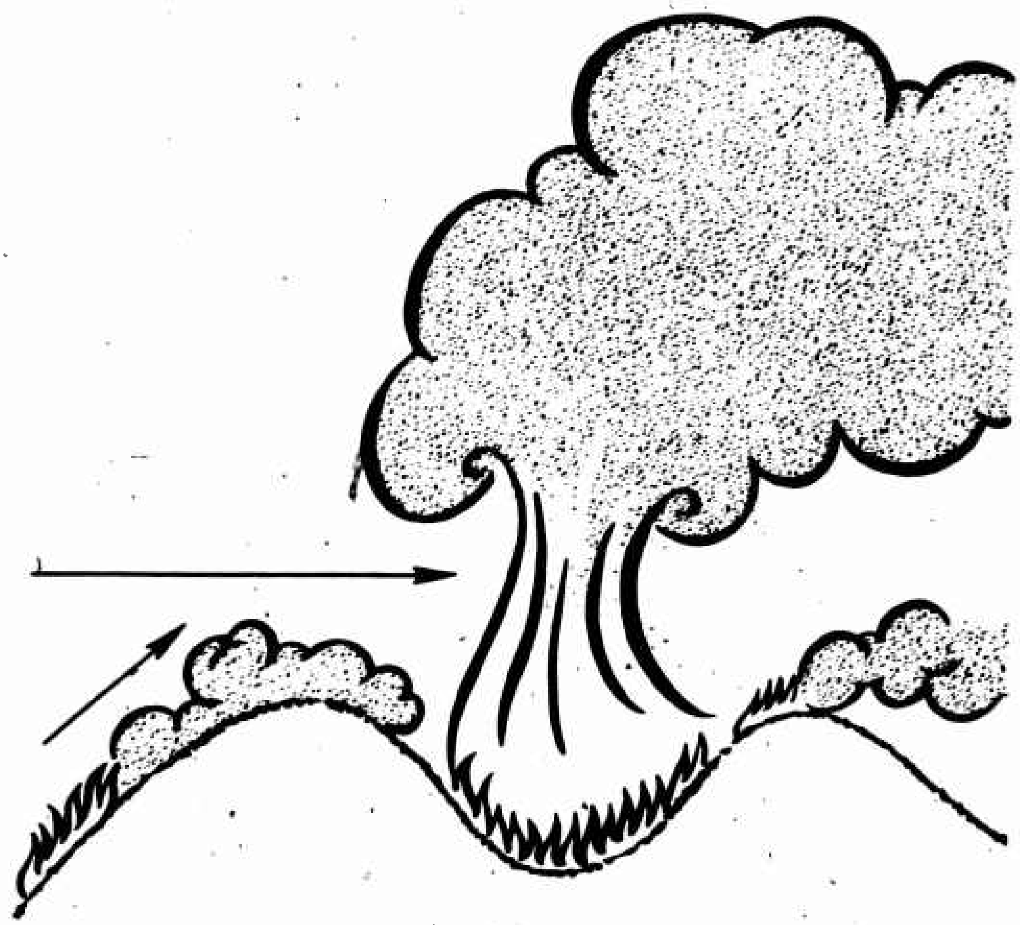

Figure 9-13. Strong winds blowing over mountain topography often cause very complex fire behavior patterns involving very rapid uphill spread, area ignition and frequently mass fire.

barren areas, which cause the fire to split and to burn around intervening obstacles. It is common for intervening areas between these separated heads to burn out as flank fires which upon joining may or may not exhibit significant interaction. In many cases, however, unburned islands of fuel may be left.

All of the fires in the above eight classes are characterized by high rates of spread, erratic fire behavior, and mass spotting, which can prove extremely dangerous to personnel and material located in front of the moving fire. The depth of fire along the fire flanks behind the fire front is usually too great to permit penetration and many of the fuel types involved have long residual burnout times, offering little protection even if accessible from the outside.

9.7 AREA IGNITION AND COALESCENCE

Multiple fire starts which interact and combine to burn out the area are known as area ignition. The interaction between fires increases the rate of combustion and heat output beyond that which would result from a single fire.

The area subjected to area ignition by a nuclear detonation may vary from a few acres to many square miles. The resulting fire behavior depends upon the fuel type and loading, the burning conditions, and the density of ignition points. Under most situations area ignition can result in the burning over of an area much more quickly and with higher intensity than could be obtained by a single fire. This is particularly true under less severe burning conditions.

Two types of fire interaction must be considered in area ignition. In very light fuels or in heavier fuels under poor burning conditions, individual fires are wind dominated and exhibit little convective activity. Separate fires thus burn independently until they have burned toward each other and are separated by a distance that varies with atmospheric instability. At this point the flames begin to interact and the fires begin to pull together. This speeds up the rate of spread, flame height, and fire intensity reaching maxima as the flames merge (Reference 7). This band is usually too narrow, however, to have appreciable significance beyond hastening up the burnout period.

Fires in heavier fuels with a higher combustion rate exhibit a different form of coalescence. In those cases which develop strong convective activity, the convection columns may join high above the surface -- as much as 2,000 feet or more -- and then interact. The degree of interaction depends on the combined energy at point of convergence. If strong enough, and no one has determined what this may be, the convergence point descends rapidly toward the surface. Hot fires a mile or more apart may then quickly accelerate toward each other with greatly increased rates of spread and intensities (Reference 8). They then meet in a veritable holocaust. The lesser of two such heat sources is the most affected. Multiple ignition sources may react the same way, all pulling toward the center of strongest convective activity. The result is commonly mass fire. Whether or not such mass fire demonstrates firestorm characteristics is more often than not governed by chance. The same applies to the possible development of strong fire whirls which in turn produce mass spotting. In most instances, however, this mass fire phenomenon results in a minimum of fire spotting and low rates of exterior spread during the burnout period.

When the ignition area is large as, for example, more than one or two square miles in area, it is most likely that more than one center of maximum convective activity will develop. The reasons for this are largely the same as those which cause multiple-head fires described under Type VIII above.

After the central area of a mass fire has burned out and there remains a continuum of fuel around the perimeter, spread may then continue as in the case of any large fire reacting to the fuel, its flammability, and the ambient environment.

9.8 MASS IGNITION

The simultaneous ignition of the tops of vegetation may take place in many extensive savanna areas of dead grass, ripened grain, lichens and mosses and the like, exposed to direct fireball radiation. Even though there may be some small misses, the general effect is the same. These areas may rarely be intended targets but will occur in many instances incidental to other effects.

In mass ignitions of this type with ignition taking place at the unshaded tops, the subsequent fire burns downward. More frequently perhaps, burning tips will fall to the ground and the fire will then burn predominately upward through the fuel mass. In either event the reaction is extremely rapid and peak fire intensities over the whole area will be attained very quickly because of the predominantly fine fuels which make up the fuel complex. Mass fire generated in this fashion is of short duration, but of sufficient intensity to be intolerable to life. Up or down drafts or oxygen deficiency may cause fire pulsation in the region of maximum shown in Figure 9-14. When it is over, remaining fires around the perimeter may then continue to spread according to the ambient environment. These fires may often provide the fuse for igniting other contiguous fuel types.

9.9 PREDICTING FIRE BEHAVIOR

Predicting quantitative rates of fire spread and other features of fire behavior in wild land vegetation complexes remains an art. It must be done at the fire site by a highly trained and experienced fire specialist who must observe a vast number of interacting parameters and evaluate them in his mind in view of existing and predicted short

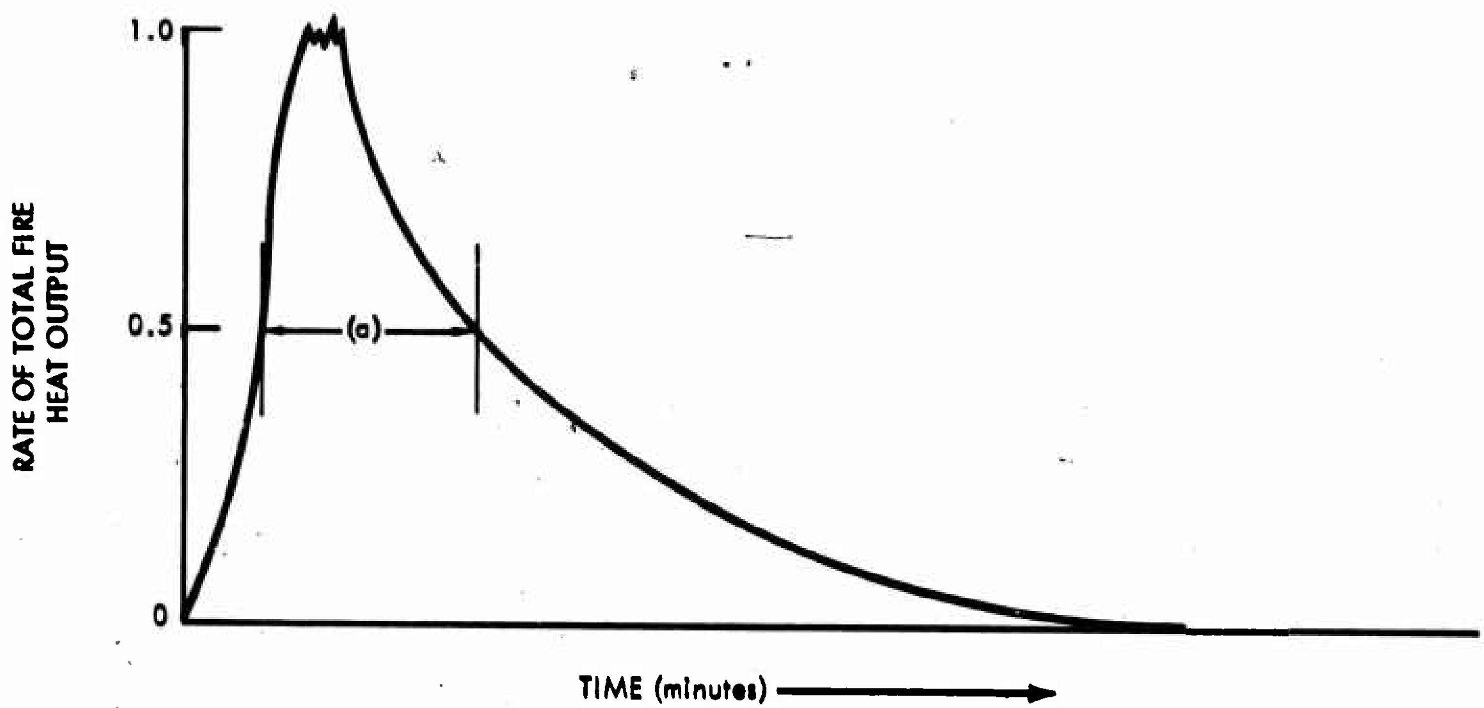

Figure 9-14. Mass ignition of fine fuels results in very rapid buildup to maximum total heat output. The interval (a) exceeding 50 percent of maximum may be as short as 1-1/2 to 2 minutes.

time changes in fuel, weather and topographic factors of environment. The reasons for this are several but the most significant is that no method has yet been developed for quantitatively describing the infinite variety of fuel parameters that govern fire behavior.

In spite of the dearth of quantitative measurements of all critical fire parameters, numerous empirical fire-danger rating systems have been developed and refined in the United States and other countries over the past 30 years.

A fire-danger rating system is a mathematical method of integrating the combined effects of a small number of known and measurable weather and fuel factors into relative index numbers related to the potential ease of fire starts, rate of spread, fire intensity, or various combinations of these fire phenomena. Their construction is based on combinations of theoretical analyses, laborator and field experiments, and the measured behavior of wildland fires. The purpose of a fire-danger rating system is to provide fire control managers with consistent day to day information on the likelihood of fire starts, rates of spread, required strength of fire attack, and for other purposes. The index numbers used are usually on a scale of 0 to 100 with 0 representing no fire danger and 100 representing average bad burning conditions. No attempt is made to evaluate those infrequent, extreme burning conditions, where fire once underway is virtually uncontrollable with existing firefighting technology.

Existing fire-danger rating systems that have been developed can sometimes be used as indicators of the need for preparedness to attack and control small fires. These are interpreted as fires well established but still in the accelerating stage and thus dominated by surface weather and fuel conditions. The question of rates and degree of acceleration applicable to different types has not yet been resolved, although Australian studies (Reference 3) indicate rate of spread to be a function of the inverse power of the time since origin.

Each existing known fire-danger rating system uses a rate of spread index as either the total or partial indicator of fire danger. Each is based on locally developed relationships between surface litter or other fine fuel moisture content, windspeed, and rate of fire spread. Anemometers mounted at a fixed height in the open are commonly used for the windspeed input. No method has yet been devised for measuring fuel moisture content directly in place and the different systems use varying methods for estimating this input from different combinations of weather and sometimes other parameters.

Some rate of spread index systems are for general application for which local modifications and interpretations are intended to be applied. Others have been developed for specific fuel situations. Two examples of the first and two of the second will be briefly described for illustrative purposes.

9.9.1 California Wildland Fire-Danger Rating

A rate of spread index is computed in this system (Reference 9) from a single table in which rate of spread indexes are tabulated on a scale of 0 to 100 corresponding to windspeeds measured at 20 feet above open level ground and surface litter and other dead fine fuel moisture contents. The rate of spread index is universal, applying to all fuel types irrespective of fuel loading or other considerations. Fine fuel moisture content is estimated by weighing a calibrated 1/2-inch pine dowel fuel moisture indicator stick which integrates recent weather events adjusted according to current relative humidity. The basic table applies to flat to gentle topography. The effects of moderate and steep slopes are read from the table by entering it with the equivalent of progressively higher windspeeds. No attempt is made in this system to interpret rate of spread index in terms of actual rates of spread. Neither is there any provision for adjusting windspeed applicable to different vegetation types.

Rage of spread indexes for selected fine fuel moisture contents have been read from the basic table and plotted in Figure 9-15 to show the general relationships portrayed by the system. These rate of spread determinations are primarily useful for evaluating fire potential only when interpreted in terms of a burning index computed separately for three broad basic fuel types -- grass, brush and timber. The burning index is essentially a combination of rate of spread and fire intensity indexes.

The grass burning index is the same as the rate of spread index for fully cured dead grass. Prior to this state the burning index is lowered in four successive steps ranging from 75 percent cured to 0 percent cured. The brush burning index incorporates an intermediate table, intensity index -- brush fuels, following the spread index table. Intensity index values on a scale of 0 to 100 are based on the days since new growth of evergreen brush vegetation and on the current fuel moisture indicator stick moisture content.

The brush burning index, again on a scale of 0 to 100, is then read from a final table for which spread index and intensity index are the

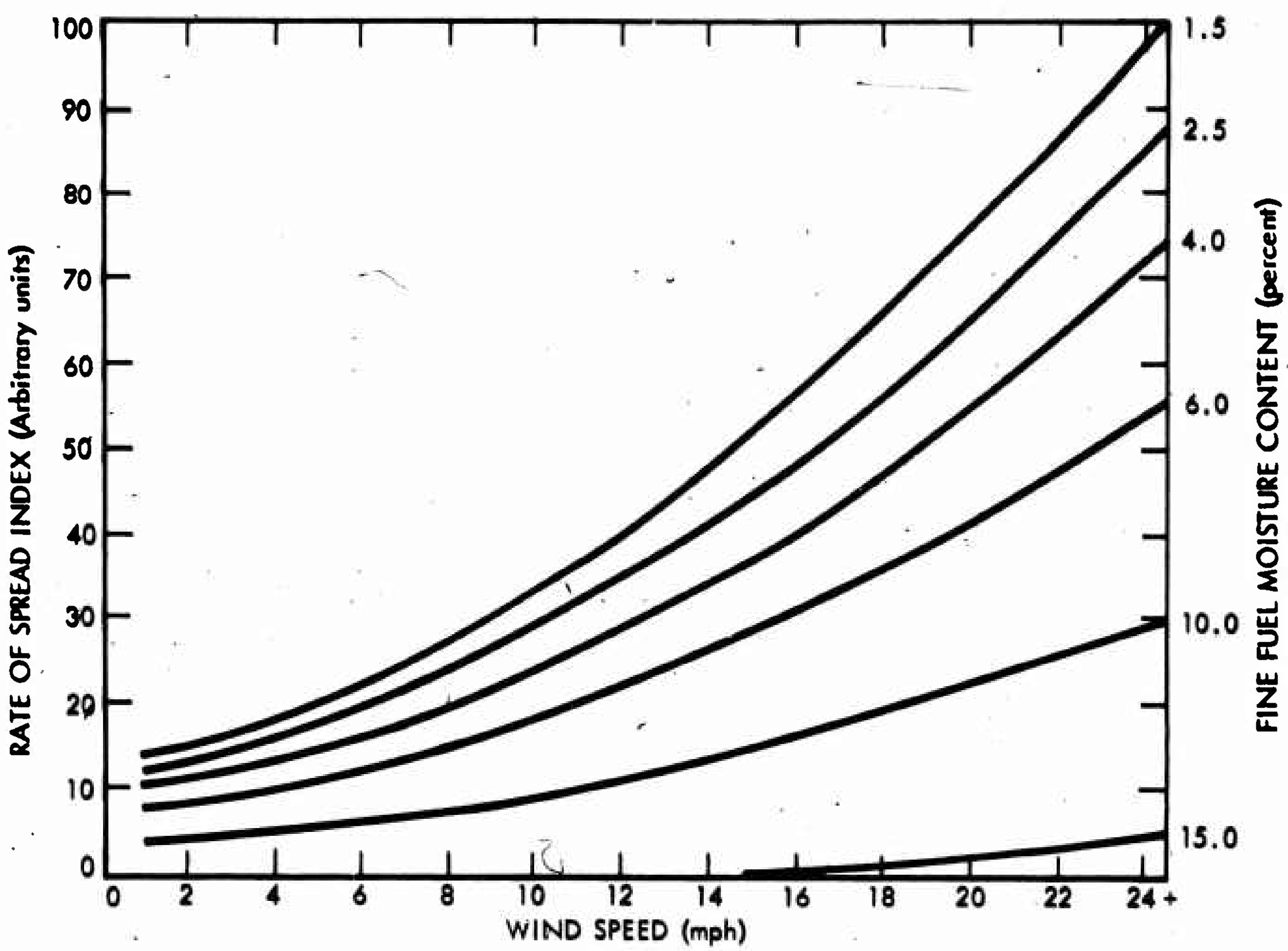

Figure 9-15. California wildland fire danger rating.

input parameters. Brush burning index values may equal or exceed spread index values at intensity index values generally above 75 up to the maximum of 100.

The timber burning index also makes use of an intermediate table, intensity index -- timber fuels. Intensity index values on a scale of 0 to 100 are read from this table which has buildup and current fuel stick moisture content as input. The buildup in this case is computed as a cumulative daily tabulation of drying factors for different fuel moisture stick moisture contents and wetting factors for different rainfall amounts. The fuel stick moisture content entry is that for the current day.

The timber burning index is then read from a final table with spread index and intensity index as inputs. As in the brush burning index, burning index values in this table also equal or exceed the spread index values when the intensity index exceeds about 75.

Burning indexes compiled in the California wildland fire-danger rating system become useful local indicators of potential fire behavior after sufficient data have been accumulated within an operational area to relate the measured indexes with wildfire experience. One reason for this requirement is that the system does not recognize species flammability differences, fuel loading, or the effects of vegetation type on windspeed and other weather factors measured in the open. It serves adequately where these relations have been established. The system could be modified to take these local factors into account.

9.9.2 Canadian Forest Fire Weather Index

This fire-weather index is a numerical rating of potential fire intensity in a standard (but undefined) fuel type (Reference 10). By definition this index is dependent on weather only, does not consider the effect of differences in fuels or slope. It provides a uniform scale for rating fire weather severity throughout Canada. It is related to the ease of ignition of wildfires and is a relative measure of expected fire behavior and daily fire control requirements. Because of its nature, however, these relationships must be determined entirely on a local basis.

The fire-weather index consists of ten tables which are grouped into six interlocking blocks as illustrated in Figure 9-16. The weather inputs to this system measured at 12:00 noon local standard time daily are shown at the top of the diagram.

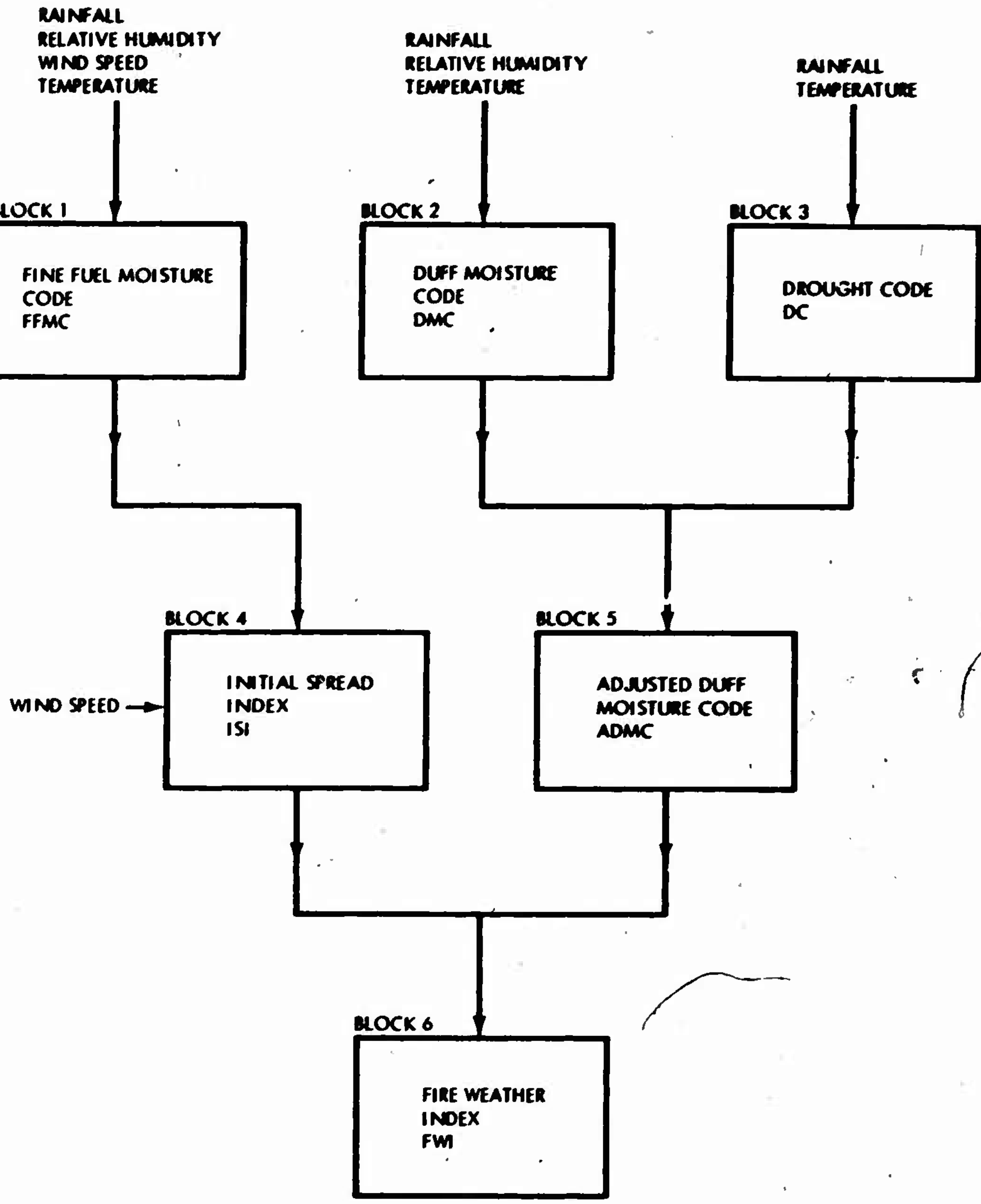

Figure 9-16. Block diagram of forest fire weather index.

This system is more complex than the California system described above but like that system both the initial spread index and the fire-weather index must be associated with local wildfire experience before they become meaningfull. The indexes employed in this system are open ended at the top rather than having a maximum of 100. The structure of the system makes it difficult to compare with others.

9.9.3 Eucalyptus Forest Fire Danger Rating

This system developed in Australia in 1958 (Reference 11, 12) as fire danger tables now appears in the form of a circular slide rule as the Forest Fire Danger Meter Mk. IV (Reference 13), similar and general appearance to the grassland fire meter (see, 9.9.4 Figure 19).

The fire danger meter integrates the combined effects of fuel moisture and wind velocity to form a basic fire danger index. This basic index can be related to fuel quantity and slope to give the rate of spread of the head fire and other fire behavior characteristics.

The fire danger index is directly related to rate of spread on a scale of 1 to 100. An index of 100 represents the "worst possible" fire weather conditions that are likely to be experienced in Australia, and may be defined by:

Air temperature 100° F

Relative humidity 10 percent

Average wind speed of 35 mph in the open measured at 10 m

An extended drought period of 6 to 8 weeks or more

Unstable atmospheric conditions

At an index of 100 fires will burn so rapidly and hotly that control is virtually impossible.

The index is sub-divided into five fire danger classes of low, moderate, high, very high, and extreme and these represent the relative difficulty of suppression of a fire in a five tone per acre eucalypt fuel type. Initial attack by an efficient fire suppression organization within 30 to 60 minutes of fire start will generally succeed up to fire danger index of 24, has a 50 percent chance up to an index of 50, but beyond this point initial attack will generally fail.

The basic relationships between the fuel moisture content of fine fuels less than one-fourth inch in diameter or thickness under prolonged drought, and wind speed in the open and rate of forward progress of the headfire are given in Figures 9-17 and 9-18. These spread rates are typical of a fire burning in a 7 ton per acre fuel type under closed canopy in a stand at least 100 feet high.

The fuel moisture content, as such, does not appear on the meter but is determined directly from temperature and relative humidity. These moisture content values are for clear sky conditions (unstable atmospheric conditions) and are based on the near equilibrium values existing from around 1300 to 1600 hours. The meter and tables tend to overestimate fire danger and rate of spread during cloudy days or in the early morning due to the time lag in the diurnal drying processes. Similarly, due to the slow uptake of moisture during the early evening, the meter may tend to underestimate the fire danger, especially on days when fuel moisture contents have reached very low values.

The fire danger index and corresponding fire behavior varies according to long and short-term drying effects. The long-term drying effects are expressed in terms of the Byram-Keetch drought Index (Reference 14). As the drought index increases, more fuel becomes available for combustion, through the drying out of large fuel componants and the reduction of moisture in the understory vegetation and this affects the fire behavior accordingly. Likewise the fire danger index varies according to the number of days since rain of specified amounts. This modification is based on two effects: First, the increase in the surface litter moisture and second (and more important) upon a reduction in the amount of fine fuels (i. e., combustable material less than one- fourth inch in diameter) available for burning.

While this rating system was developed for a particular fuel, and the fire behavior characteristics for eucalypt fuels have been determined (Table 9-2), the basic fire danger index is derived from the major variable fire danger factors and these relationships are fundamental for fires burning in forest litter types. Differences in the constant fire danger factors such as fuel quantity, fuel distribution and fuel compaction, slope, aspect, etc. will mean that although the fire behavior in different fuel types such as conifers or deciduous hardwoods will differ from the fire behavior in a dry sclerophyll eucalypt forest; it can be directly related to the basic fire danger index (Reference 15).

Data is for a well-stocked eucalypt forest 100 feet high containing a high proportion of fibrous barked trees and so has a high spotting potential.

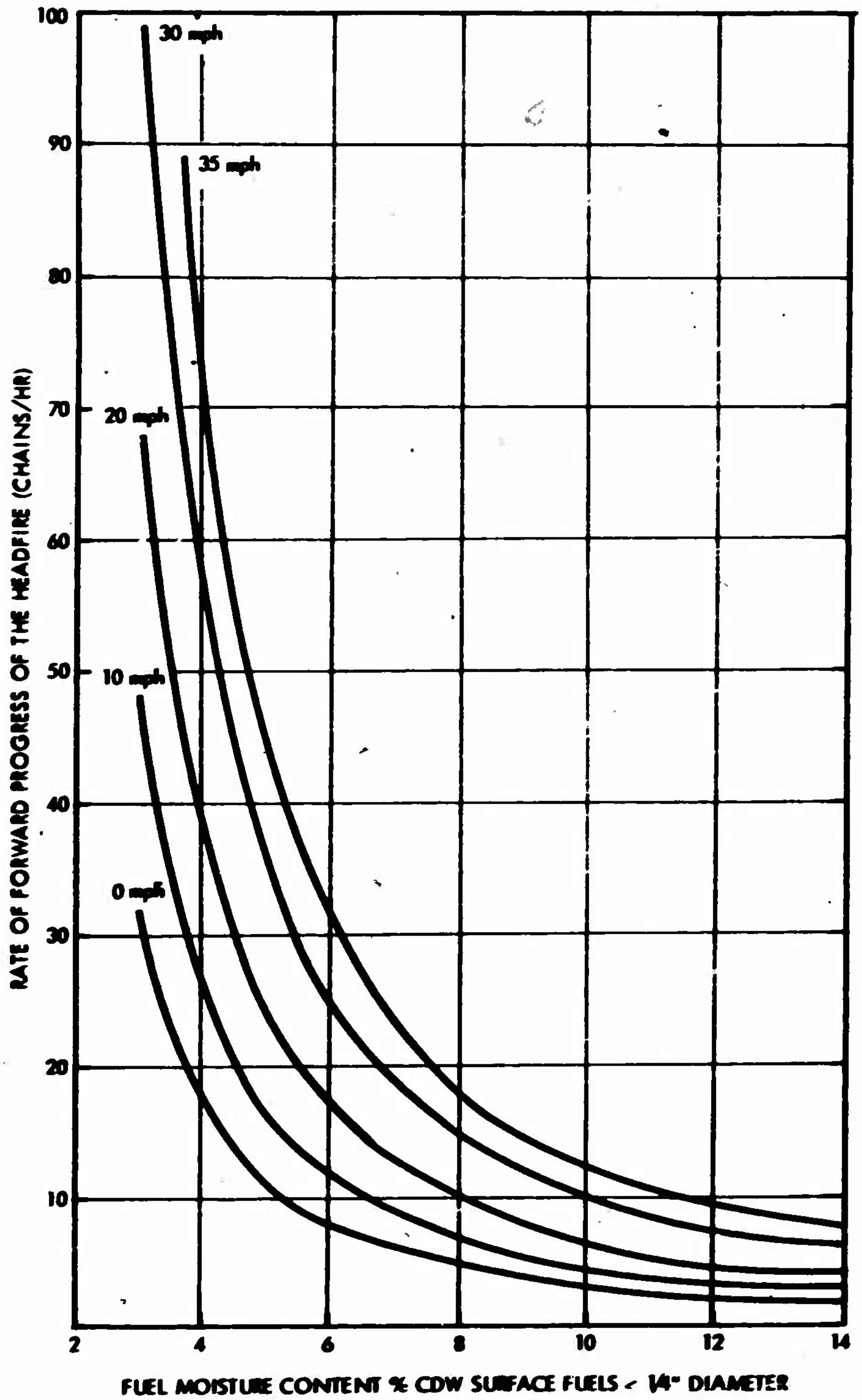

Figure 9-17. Rate of spread of the headfire in a 7 TPA eucalypt fuel type related to fuel moisture content and wind speed of 0, 10, 20, 30, and 35 mph in the open at 10 meters closed forest canopy with stand height of 100 feet (derived from Forest Fire Danger Meter Mk IV).

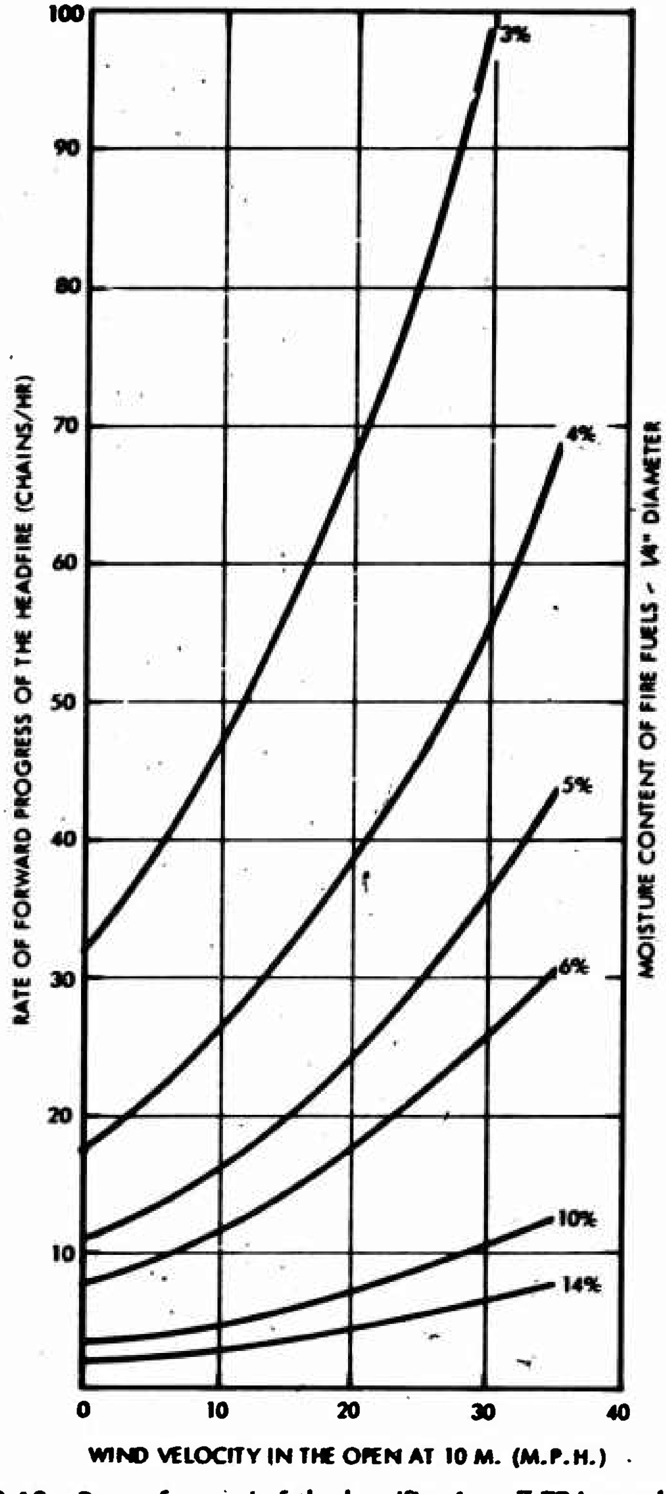

Figure 9-18. Rate of spread of the headfire in a 7 TPA eucalypt fuel type related to wind velocity in the open and surface fuel moisture contents of 3, 4, 5, 6, 10, and 14 percent.

Table 9-2. Expected fire behaviour in eucalypt fuels for various fire danger indices.

Fuel Quantity (tons per acre)	Fire Behaviour	Fire Danger Index 5	10	20	40	60	100
3	R*	2	4	9	18	26	45
	H	2	5	8	15	20	29
	S*	—	—	15	45	80	140
5	R	4	7	14	28	42	70
	H	4	8	16	28	39	Crown Fire
	S	—	5	30	80	14	240
7	R	5	10	21	42	63	105
	H	7	15	27	48	Crown	Fire
	S	2	15	50	130	200	360
10	R	7	15	30	60	90	150
	H	10	22	40	Crown ←	→	Fire
	S	5	30	80	180	280	480

Note: R = rate of forward spread in chains per hour.
H = flame height in feet.
S = average spotting distance in chains.
Fuel quantity is expressed in tons per acre of combustible material less than one-fourth-inch diameter.
*1 chain = 66 feet.

In low quality stands of eucalypts where the height of the stand may range from 30 to 50 feet and the tree canopy is more open, rate of spread will be greater than those given in Table 9-2 due to the fact that much higher wind speeds will be experienced at ground level.

Taking the ecological situation even further, low quality eucalypt stands which may have a continuous forest canopy then tend to merge into eucalypt savannah woodland types where the ground cover is predominantly grasses and herbs. In this situation the fire behavior is best expressed by the grassland fire danger meter using a reduced wind speed.

The fire danger index on the meter is expressed as a logarithmic scale and the index number is directly related to rate of spread, ignition probability and suppression difficulty. Area burnt and damage potential is a power function of the index number.

The rate of spread and other fire behavior characteristics given by the Forest Fire Danger Meter Mk. IV are typical of single fires burning under commercial eucalypt forests and cannot be used to predict the behavior of multiple fires burning in close proximity to one another.

In simple terms, little interaction will occur between multiple fires burning in a 5 to 7 tons per acre fuel type when the fire danger index remains below 5, even at an ignition density of 6400 per square mile (1 x 1 chain interval) whereas a mass fire effect will generally result at an index of 12 for this ignition density. However if the ignition density is only 256 per square mile (5 x 5 chain interval) little or no interaction will occur at an index of 12 and a mass fire effect will not result until the index rises to around 20.

Fire behavior tends to become violent once the forest fire danger index rises above 24, especially in a multiple fire situation and suppression forces would have little chance of success. Survival becomes the main consideration, not extinguishment.

The scaling-up of fire behavior from a singel fire to a multiple fire situation is complex and far beyond the limitations of the forest fire danger meter. Multiple fire behavior is controlled essentially by the ignition density, fuel loading and distribution, combustion rate of the fuel, and atmospheric instability. All that can be said is that personnel would be relatively safe in a multiple ignition situation up to an index of 5. From this point onwards their chances of survival would depend on the ignition density and fuel characteristics of the forest.

9.9.4 Grassland Fire Danger Rating

The Grassland Fire Danger Meter Mk. III (Figure 9-19) was designed for use in relatively fine textured annual grasses in Australia, (Reference 16) and replaces the previously used grassland fire danger tables (Reference 17).

The meter integrates the variable fire danger factors of grass curing stage, air temperature, relative humidity and average wind speed in the open to give a fire danger index ranging from 1 to 100. The Mark III meter also reads directly the corresponding rate of

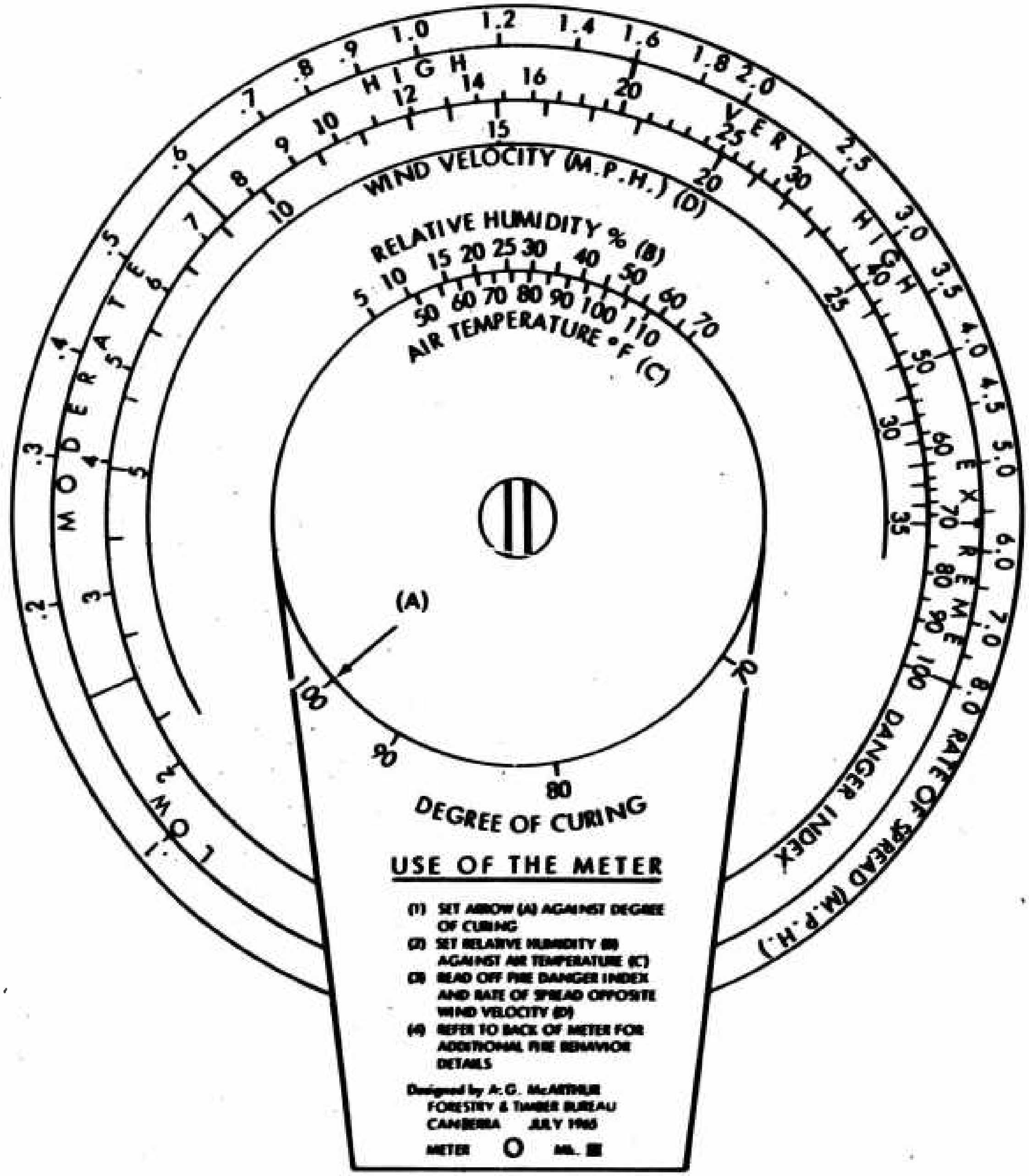

Figure 9-19. Grassland fire danger meter.

spread in miles per hour expected in fairly dense stands of improved pastures carrying a total fuel loading of 3 tons per acre. At this loading the rate of spread is equal to the danger index multiplied by 0.08. In a light fuel loading of 1 ton per acre the rate of spread is equal to the index multiplied by .03.

The rate of spread in a specific grass fuel is directly proportional to the fuel quantity, so that fire will spread faster in heavy fuels. However the finer the grass particles the faster a fire will spread and in practice it appears that changes in fuel quantity are often associated with a change in grass species and grass fineness so that the two effects tend to cancel out.

The meter was not designed for use in the coarse thick bladed perennial grasses as found along coastal subtropical regions although it has been found that the fire behavior and rate of spread of these and coarse tropical grasses can be correlated directly with the fire danger index. To illustrate the use of the meter the slide rule was set for 100 percent cured grass and temperature of 80° F. The relative humidity disc was rotated through different settings from 5 to 70 percent relative humidity and danger indexes were read corresponding to different wind speeds; these were then plotted in Figure 9-20.

The grassland fire danger rating system, like the forest fire danger rating system, represents rate of spread as a function of wind speed raised to a power of approximately 2. However data from well documented wild-fires in Tasmania in 1967 has shown that rate of spread in fine grasses is a function of wind speed to the power 2 up to a wind speed of 28 mph. Above wind speeds of 28 mph the rate of spread decreases rapidly and it appears that for most annual grasslands, fire spread would not be sustained at wind speeds above 45 mph (Reference 18). It appears that under conditions of very strong wind the head fire becomes very narrow and tends to fragment into a series of narrow tongues of fire, many of which are self extinguishing. Although this phenomenon was observed only on very fine annual grasses it would be expected that the same trend would occur in coarser grasses but at a higher wind speed.

As with the Forest Fire Danger Index Mk. IV the index on the grassland meter is expressed on a logarithmic scale and the index number is a direct linear relationship with rate of spread, ignition probability and suppression difficulty.

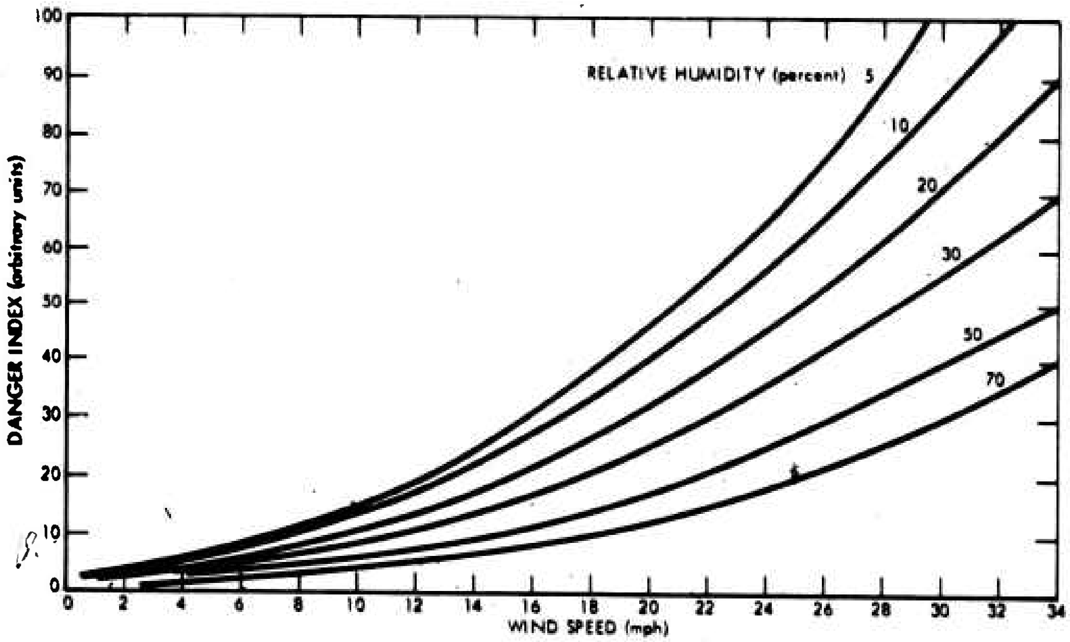

Figure 9-20. Grassland fire danger—Mark III. Grass cured temperature, 80°F.

In the coarser fuels and heavier fuel loadings under forest conditions, fuel moisture content is the most significant variable in determining fire behavior, with open station wind speed of lesser importance.

In the fine textured grass fuels, fully exposed to solar radiation and wind velocity, wind speed becomes much more important than fuel, moisture content and a fire in dense, fully cured grasslands will spread rapidly under strong wind speeds at very low temperatures and relatively high humidities.

Interaction between multiple fires is slight while the index remains below 7 but increases rapidly as the index rises and depends on the ignition density and fuel loading. Multiple fire behavior would become violent at indices above 20 and survival of field personnel difficult, but not nearly as critical as in a forested environment. Burnout time of grass fuels is measured in seconds compared to minutes for forest fuels and more than adequate protection is provided by vehicles and even rough and ready survival shelters.

9.9.5 Relationships

It is evident from the above that additional research is needed to produce a fire prediction system for general application in all vegetation types and climatic regions. It is also evident that the first phase should concentrate on fuel ignitability and the early stages of subsequent fire behavior. It is suggested that for both purposes early effort be devoted to evaluation problems of the top litter and associated live and dead vegetation. Existing methodology needs to be extended with respect to effects of vegetation on microweather, particularly the effects on windspeed (Figure 9-21) (References 19, 20, 21, 22).

The ignition of tinder fuels by the thermal pulse is a function of fuel thickness and moisture content as indicated in Chapter 4. Moisture contents of these fuels can be satisfactorily estimated by the procedures described in Chapter 8. Table 9-3 (Reference 23) indicates the thicknesses of a variety of such tinder fuels but needs expanding and dividing into appropriate thickness classes for application. (See also Table 4-5.)

The same estimates of moisture content of surface litter fuels tempered by the amount and condition of associated living vegetation are adequate for rate of combustion and spread estimates. A technique for coupling and defining the interrelationships between surface fuel fineness, porosity and loading needs further development. Table 9-3

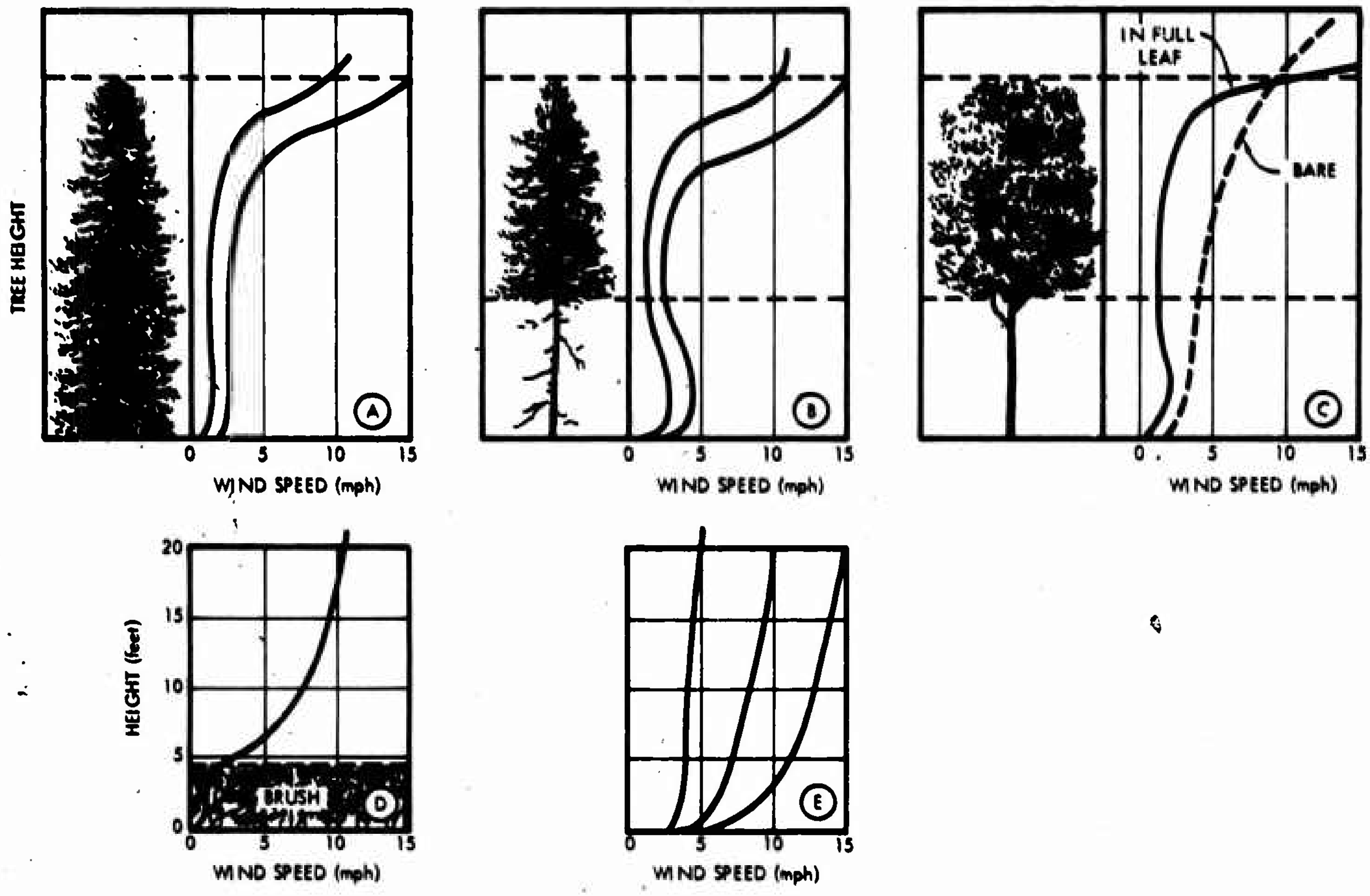

Figure 9-21. Wind speed in the flame zone is modified by the nature of the vegetation: (A) conifer forest with full canopy; (B) pruned conifer forest (C) oak-beech forest; (D) brushfield; (E) short grass. (A and B for two windspeeds, E for three windspeeds.)

Table 9-3. Average thickness and surface/volume ratios of selected forest fuels.

Material	Thickness (mils)	S/V[a] (in^2/in^3)
Horsehair lichen (Alectoria sp.)	0.787	2,500
Cheatgrass (Bromus sp.)	1.181	1,700
Desert stipa (Stipa sp.)	2.756	720
Wiregrass (Aristrida sp.)	2.756	720
Harding grass (Phalaris sp.)	5.905	340
Sedge (Carex sp.)	6.693	300
Wheatstraw (Triticum sp.)	14.576	138
White bursage (Franseria sp.)	4.331	460
Jointfir (Ephedra sp.)	4.724	420
Rhododendron (Rhododendron sp.)	9.842	204
European beech (Fagus sp.)	3.150	630
American beech (Fagus sp.)	3.543	560
Dogwood (Cornus sp.)	3.947	510
Red Maple (Acer sp.)	5.118	390
Chestnut (Castarea sp.)	5.512	360
Walnut (Juglans sp.)	5.512	360
Sourwood (Oxydendrum sp.)	6.099	330
Hickory (Carya sp.)	6.099	330
Post oak (Quercus sp.)	6.493	310
Chestnut oak (Quercus sp.)	6.887	290
Scarlet oak (Quercus sp.)	6.887	290
Madrone (Arbutus sp.)	11.054	230
White pine (Pinus sp.)	14.951	320
Ponderosa pine (Pinus sp.)	15.344	260
Scotch pine (Pinus sp.)	17.323	230
Redwood (Sequoia sp.)	18.110	220
Short leaf pine (Pinus sp.)	22.835	175
Coulter pine (Pinus sp.)	25.984	160
Norway spruce (Picea sp.)	33.071	121
1/8-in. twig	125.0	32
1/4-in. twig	250.0	16
1/2-in. twig	500.0	8

[a] To convert to ft^2/ft^3 multiply by 12

also indicates fuel fineness expressed as surface/volume ratios for the individual materials listed, but how to evaluate the fineness of fuel mixtures as found in nature has not been explored. Porosity of the fuel when measured as a volume of voids divided by the surface area of the fuel occupying a given volume has been studied for simple fuels in the laboratory (Reference 24). Preliminary results showing the product of fineness and porosity as a dimensionless number markedly affect their fire behavior. Ways to evaluate the porosity of the mixed fuels and how to relate fineness and porosity with fuel loading have yet to be defined.

The loading of surface fuels may be determined by direct sampling or on a less intensive scale by estimating the annual litter fall, its rate of decomposition and, where applicable, the rate and degree of compaction as by snow. Living surface flammable vegetation can also be sampled or more grossly estimated from knowledge of the character and growth habits of the vegetation involved. Sampling on an operational area basis for either must be quite intensive to derive data more useful than those derived by an experienced estimator.

Numerous investigatore have sampled the litter beneath typical forest stands (References 25, 26, 27, 28). Some have separated out the loosely compacted surface layer (the weight desired) while others have sampled annual litter fall and total organic accumulation on the forest floor. Both direct measurements and derived estimates have been combined in Table 9-4 to indicate typical surface litter weights.

Similar inventories have been made for a limited number of savanna and shrub types (References 29, 30, and 31). In all of these the flammable surface litter and associated vegetation were inventoried by spot sampling. Typical litter weights and total flammable fuel loading for selected United States types are shown in Table 9-5.

The importance of fuel loading in addition to its indirect relationships to fuel continuity and porosity lies primarily in its effect on fire intensity reflected in flame height. The combination of these effects also influences rate of fire spread through complicated interrelationships with wind and fuel moisture.

The additional surface fuel loading that may result from forest blowdown or defoliation may be estimated using existing techniques. The most simple method requires a tree count for an area, or sample area, by diameter classes and by species or groups of species. From such a

Table 9-4. Typical oven-dry weights of surface litter on the forest floor.

Some U.S. data include unidentified small amounts of intermixed living vegetation.

Species or Association	Locality	Surface litter (tons per acre)
Beech	Germany	3.3
Birch, Maple, Spruce	N. H.	5.0
Birch, Maple	Minn.	4.5
Spruce, Fir, Birch	Minn.	3.6
Aspen	Minn.	2.5
Mixer Broadleaf	So. Appalach.	5.0
Eucalyptus	Australia	12.0
Tropical Rain Forest	SE Asia	2.0
Monsoon Forest	SE Asia	2.2
Norway Spruce	Germany	3.2
Red Pine	Lake States	2.6
Jack Pine	Lake States	1.7
Shortleaf Pine	Missouri	4.0
Shortleaf Pine	SE U.S.	2.9
Longleaf Pine	SE U.S.	5.0

Table 9-5. Oven-dry weights of litter and flammable surface vegetation for selected savanna and shrub types.

Species or Association	Avg. height (feet)	Fuel loading (tons/acre)	
		Litter	Total live & dead
Southeast U.S. coastal			
wiregrass	2	2.9	4.5
reeds	7	4.0	10.1
reeds	10	4.7	13.2
reeds - grass	4	2.4	6.4
reeds - brush	5	4.0	8.7
grass - brush	4	3.5	6.4
brush	4	2.4	6.4
brush - grass	5	4.6	9.4
brush	11	5.0	14.0
brush - swamp	14	5.4	16.1
California Mediterranean			
wild oats - fescue	3	0.7	2.0
California sage	4	6.6	13.2
Chamise - buckbrush	4	5.3	13.7
Scrub live oak	7	5.9	23.3
Other shrub			
No. Calif. brush	5	5.0	24.5

compilation weight of the tree foliage, the principal contributor to fuel loading, may be calculated by the equation:

$$W = a(Dbh)^b$$

where:

Dbh = tree diameter at breast height

a and b = constants obtained by sampling

This equation plots as a straight line on log-log paper. Pooled data from several sources (References 32, 33, 34, 35, and 36) showing the equations used to calculate individual tree foliage weights (and some total crown weights) are shown in Table 9-6.

The tabulated sample is too small for general application. It does indicate, however, that there is sufficient similarity between some species that, when plotted on graph paper, common data can be applied to groups of species without greater error than that generally attainable without intensive forest sampling. Where applicable, this would permit estimating the number of trees per acre in mixed stands by diameter classes without reference to individual species. In adding this additional fuel loading to that already in place, special consideration must also be given to the flammability characteristics discussed in Chapter 8.

The following is a partial list of areas of major uncertainty in sophisticated fire prediction, thought field commanders obviously cannot wait for such technological advances.

1. Tinder ignitability.
2. Forward rate of spread of surface fires.
   Present technology needs to be augmented by further information on:
   a. How to measure fuel fineness and porosity of mixed natural fuels.
   b. How to integrate their effects with that of fuel loading.
   c. How to evaluate fire acceleration.
3. Burnout time for a specified area and ignition density.
4. The contributed total rate of heat output by deep litter and large dead fuels.

Table 9-6. Oven-dry foliage and total crown weights for selected tree species.

Species	Location	Pounds per tree	
		Foliage	Total Crown
Silver Maple	SE U.S.	$.066\ Dbh^{2.544}$	$.413\ Dbh^{2.558}$
Sweet Birch	SE U.S.	$.243\ Dbh^{1.928}$	$1.113\ Dbh^{2.118}$
Pignut Hickory	SE U.S.	$.101\ Dbh^{2.372}$	$.420^{2.582}$
Amer. Beech	SE U.S.	$.311\ Dbh^{2.048}$	$.827\ Dbh^{2.552}$
Yellow Popular	SE U.S.	$.188\ Dbh^{1.775}$	$.933\ Dbh^{1.781}$
Scarlet Oak	SE U.S.	$.116\ Dbh^{2.284}$	$.250\ Dbh^{2.740}$
Canyon Live Oak	California	$.044\ Dbh^{2.66}$	
White Pine	Switzerland	$.073\ Dbh^{2.09}$	
White Pine	Vermont	$.086\ Dbh^{2.32}$	
Douglas Fir	Switzerland	$.150\ Dbh^{1.96}$	
Red Pine	Vermont	$.140\ Dbh^{2.56}$	
Jack Pine	Lake States	$.055\ Dbh^{3.01}$	
Pond Pine	SE U.S.	$.486\ Dbh^{1.697}$	$.369\ Dbh^{2.390}$
Loblolly Pine	SE U.S.	(35 percent)	$.267\ Dbh^{2.538}$
Ponderosa Pine[a]	California	$.294\ Dbh^{1.41}$	

[a] Tree data are also available (Reference 33) from which equivalent computations can be made for an additional 8 conifers in Western U.S.

New technology is needed to:

a. More accurately and readily determine the extent and depth of drying, and

b. Moisture content-combustion rate relationships.

5. A guide to crowning potential.

6. Spotting potential.

7. Importance of atmospheric stability.

In the foreseeable future there is little prospect of predicting the behavior of a fast spreading crown fire in timber over any extended period of time. There is reasonable probability, on the other hand, that current onsite observations can lead to the prediction of area burnout time where two or more crown fires may burn together. Although other factors can usually be estimated well enough for many field situations, spotting remains an area of major uncertainty.

9.10 SUMMARY

This chapter has briefly described a broad spectrum of fire phenomena of primary concern to field operations and some of the principles underlying them. It has indicated the exceedingly complex interactions between fire and environment that must be quantitatively evaluated in assessing any fire situation with useful accuracy. And although a few examples have been given of practical field measures, and how they are currently interpreted with respect to potential fire behavior, primary emphasis still remains on those environmental factors known to regulate combustion phenomena but for which there are no present means for measuring or evaluating in field practice. It is in these areas in particular that the fire behavior specialist must still practice his art. Presence of such a specialist on military staffs is highly desirable for operations in forested areas.

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CHAPTER 10

FIREFIGHTING AND EVACUATION*

10.1 INTRODUCTION

Firefighting is a defensive measure to be undertaken whenever essential to protect personnel, equipment, and materiel, or other assests from the fire effects and also to insure maintenance of protective cover and routes of travel and communication.

Firefighting in field operations must always be adapted to circumstance determined by a quick estimate of the situation by the field commander. This in turn requires fast ground intelligence with respect to area involvement, density of fire starts, availability of troops for fire attack without aborting the military mission, radiation hazard, and other details. This should be quickly followed by a continuing aerial reconnaissance, preferably by helicopter, to maintain a continuous flow of information needed for followup strategy; infrared sensors are indispensable for penetrating smoke cover, critical fire situations are, of course, limited to one or two months per year in any given locality, and the these months are usually well known.

10.2 ACTION ALTERNATIVES

The commander will ordinarily be limited by these circumstances in his choice of alternatives; however, he may be able to decide forthwith, for example:

1. Available forces can reach starting fires in time to put them out while small.

2. Density of ignition points in an area exceeds the capabilities of ground forces for reasonable attack.

3. One or more fires quickly develop into a moving fire front.

4. Residual and early fallout radiation may demand immediate rescue and evacuation without major firefighting effort.

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* This chapter describes only emergency military actions, not the art of fire suppression. The latter is the field of a professionally trained fire suppression strategist.

10.3 PUTTING OUT SMALL FIRES

If the decision is reached to put out fires while they are small, it is of prime importance to remember that speed is the essence of fire control. Since the beginnings of organized fire protection, a legendary saying has been that one man arriving at an incipient fire is worth a thousand men after it has passed through the acceleration and transition stages. Therefore, immediate detection and dispatch to every ignitable feasible must always be the first order of business whenever the numbers of available personnel can reasonably match the numbers of fire starts within required time limits. These limits will vary primarily according to fuel type and burning conditions of the moment that determine the rates of fire buildup and spread, and there may be situations, largely determined by weather, when suppresion activity is not needed or feasible. It is common practice in grazing country to ignite many small fires during prescribed burning seasons without first removing the cattle; thus it is obvious that, under proper conditions, wartime ignitions can be virtually ignored.

The containment of small fires is always by extinguishment in order to prevent their coming back to life and spreading at a later time. This will often present a severe challenge to untrained men without sophisticated firefighting equipment normally available to professionals. It requires ingenuity, a cool head, and willingness to take quite a beating. When the time comes for action, there will be no time left for instruction. The steps are simple: stop the spread, knock down remaining flames, then mix the hot remains with cooling dirt and stir the whole mix with the fingers to assure no embers remain. The tools with which to do all this are at most, hands, feet, entrenching tool or any other handy thing that will help dig or scrape. In light fuels a green branch with foliage is often useful for sweeping flame back into the burning area while stomping with the feet along the fire edge. Whatever the attack, it must be aimed at separating flame from the unburned fuel and always as close to the flame front as one can work at the expense of some singeing. When this first step is accomplished, one choked and blinded by smoke may take a breather, but not before.

The one-man attack rule stated above is universal but of course more men for attack is always advisable if there are enough to go around.

10.4 AREA-IGNITED FIRE

Whenever it becomes evident that the numbers of fire starts exceeds the capabilities of available forces for immediate suppression, or if such suppression action should fail because of the aggressiveness of individual fires, immediate decision must be made to sacrifice the area to fire and proceed with its orderly evacuation (see, 10.6). Time will ordinarily preclude the possibility of evacuating anything which is not already mobile. When this action has been initiated, establish an assembly area sufficiently removed from the expected burnout area, reassemble and continue the mission.

Subsequent containment of the fire in areas not under enemy pressure should be assigned to Engineer Units with their heavy equipment and other necessary firefighting gear.

10.5 FIRE WITH MOVING FRONT

A single fire, originating from one or more fire starts, that is spreading with a moving fire front usually presents several potential courses of action. If the fire front is moving directly and rapidly toward the occupied area, the only recourse except in the lighter fuels is to evacuate to one side or the other. No firefighting tactic will prevent the fire from overruning the area. In which direction to evacuate will be determined by the tactical situation, availability of favorable egress routes, topography and other factors that will be apparent at the time. Withdrawal ahead of the advancing fire front is extremely hazardous and should be attempted only as a last resort. If, on the other hand, it is evident that the fire front will pass to one side or other of the occupied area, additional choices are available. If the unit has no firefighting capability, it can either evacuate in the direction away from the fire's edge or, in the case of light fuels, wait until the head of the fire has passed then get inside of the burned area, or in a burned out area the unit can go downwind. In the event that motor vehicles are available and especially tracked vehicles, they may be assigned to building a fire line on the fire side of the occupied area by dragging logs or any other available heavy objects which will gouge a line down to mineral soil. This step is, of course, not necessary if there is already a bare area around the occupied perimeter. This tactic can be employed in heavier fuels as well as grass. After the fire front has passed, this line may then be quickly backfired (see, 10.7) toward the flank of the passing fire. (In many usages the term "backfire" is equivalent to "burnout".) This operation can be accomplished in a short time and requires a minimum of manpower diverted from the unit.

10.6 EVASIVE ACTION IN THE EVENT OF UNCONTROLLABLE FIRE

Evacuation has been mentioned briefly in the above paragraphs. It is not always a simple task, especially in areas with numerous fire starts underway. In most cases, it is preferable to take more positive action. Firefighters have many safety rules for their own protection. Only those most pertinent to military units and the potential situations in which they are likely to find themselves are noted here:

1. Possible tactical withdrawal routes should be planned in advance just as are escape routes planned for the evacuation of personnel in the face of overwhelming enemy action. The fastest travel routes come first to mind, but there are times when they are no more useful than slower routes through areas with less flammable vegetation. Especially dangerous are close-grown forests susceptible to rapidly spreading crown fires, with heavy fuel accumulations on the ground. The proximity of canals or rivers in which personnel can submerge and, thus, survive fire is another consideration, along with the use of bunkers, trench systems, or freshly bulldozed areas.

2. When fire occurs determine the locations of the threatening fires, how they are behaving and how they can be expected to behave during the time required for evacuation.

3. Be prepared to backfire excape routes about to be cut off by individual running fires (see, 10.7). This is not expected to have any effect on the ultimate fire behavior but is a temporary holding action, designed to slow down the rate of advance of the fire front.

4. Avoid concentrations of men and machines likely to lead to congestion and halted traffic. Get any disabled vehicles out of the way and abandon them immediately.

5. Avoid routes along slopes up which fire may spread from below. Such spread may be extremely rapid and there is no defense against it. Backfiring downhill against such a spreading fire only causes it to increase its pace.

10.7 BACKFIRING TECHNIQUES

Backfiring by military personnel must be considered an emergency measure only to be used as a last resort. The reason for this is that it is risky at best and combat troops are neither trained nor equipped for this type of firefighting as are professional firefighters. Only the most rudimentary actions in this area should therefore be attempted.

In these situations only a few simple rules are applicable (see Figure 10-1).

1. In backfiring, or burning off, the perimeter of an occupied position against an encroaching side of a fire in which the fire front has moved by:

a. Start igniting the surface fuel at the end of the cleared area nearest to the head of the fire. After starting this fire, wait a moment to see how it behaves. If the fire begins to spread in a direction parallel to the main fire axis, it may be necessary to start additional fires 20 to 30 feet toward the main fire from the fire line to start pulling the backfire towards the main fire. As these fires build up and the fire dies down along the fire line, continue igniting the line back towards the rear end of the fire or occupied area (Reference 1). Unless the wind is blowing appreciably toward the main fire, carry the fire along slowly to prevent too much heat buildup next to the fire line while the fire burns inward away from the prepared line.

b. The fuels to be ignited in this manner are grass or surface litter fuels in which the fire will spread most rapidly but if these are overtopped by shrub fuels of significant density, every attempt should be made to get these to burn as well. Fuel types in which extreme care must be taken consist primarily of conifer trees in which the crowns, dead branches or draped moss extend down close to the surface fuels. These are likely to cause crowning immediately and unless the wind is significantly strong away from the protected area, the results may be extremely troublesome.

c. The time of day in which such burning should be done is often important. The high moisture contents of fine fuels in early morning or at night may cause the backfire to produce little heat and not burn clean. Convective activity and interaction with the advancing fire which should help draw the backfire toward it are also at a minimum during these least favorable hours.

d. How to ignite the backfire and carry it along the fire line may often prove to be a problem. The supposition here is that matches only will be available. In this case, start the fire by putting together a small pile of litter or other light material, ignite it, and then use this burning material for starting additional fires. Once on fire, these materials can usually be spread by dragging along the burning litter with branches, use of the feet, or any other small tool that might be available. If the initial pile of litter cannot be lighted with a match, the chances are that the fire will not succeed as an effective backfire.

e. Once the backfiring is well underway, carry it back along the fire line as rapidly as conditions permit and extend it far enough to the rear of the occupied area to assure against ultimate fire encroachment. Caution: Use of gasoline to accelerate fire spread is extremely hazardous and should be undertaken only under dire circumstances.

2. In backfiring to protect escape routes from running fire fronts:

a. It is assumed that the escape route consists of a road, trail, or other already cleared line because in this case there will be no opportunity to construct one.

b. Burn out this line as in the example above except that it is most desirable to start the fire at the projected axis of the fire front and then spread fire in both directions far enough to block the fire front.

c. The initial wind may be adverse to the backfiring operation but as the main fire approaches it will ordinarily draw the backfire toward it. Do not worry about spot fires across the line.

d. A variant of this method, in light to medium grass fuels (or even forests under ideal conditions), is to string out fire not as a backfire but as one intended to burn in the same direction as as the main fire. As this fire advances, move into the burned area and follow the flame front as closely as possible. The main fire will split and burn around both sides of this burned area and finally permit escape through the lesser intensity fire flanks.

10.8 NUCLEAR FALLOUT FACTORS

This chapter has discussed fire containment and evasive action alternatives in the absence of nuclear radiation hazards. While mentioned last, these hazards must be of first concern in the selection of any of these alternatives and require constant monitoring as well as early prediction of local fallout patterns.

These nuclear radiation hazards are discussed in Chapter 5. Note particularly that the pattern of residual radiation may be altered considerably by the occurrence and behavior of fire in fallout areas. It

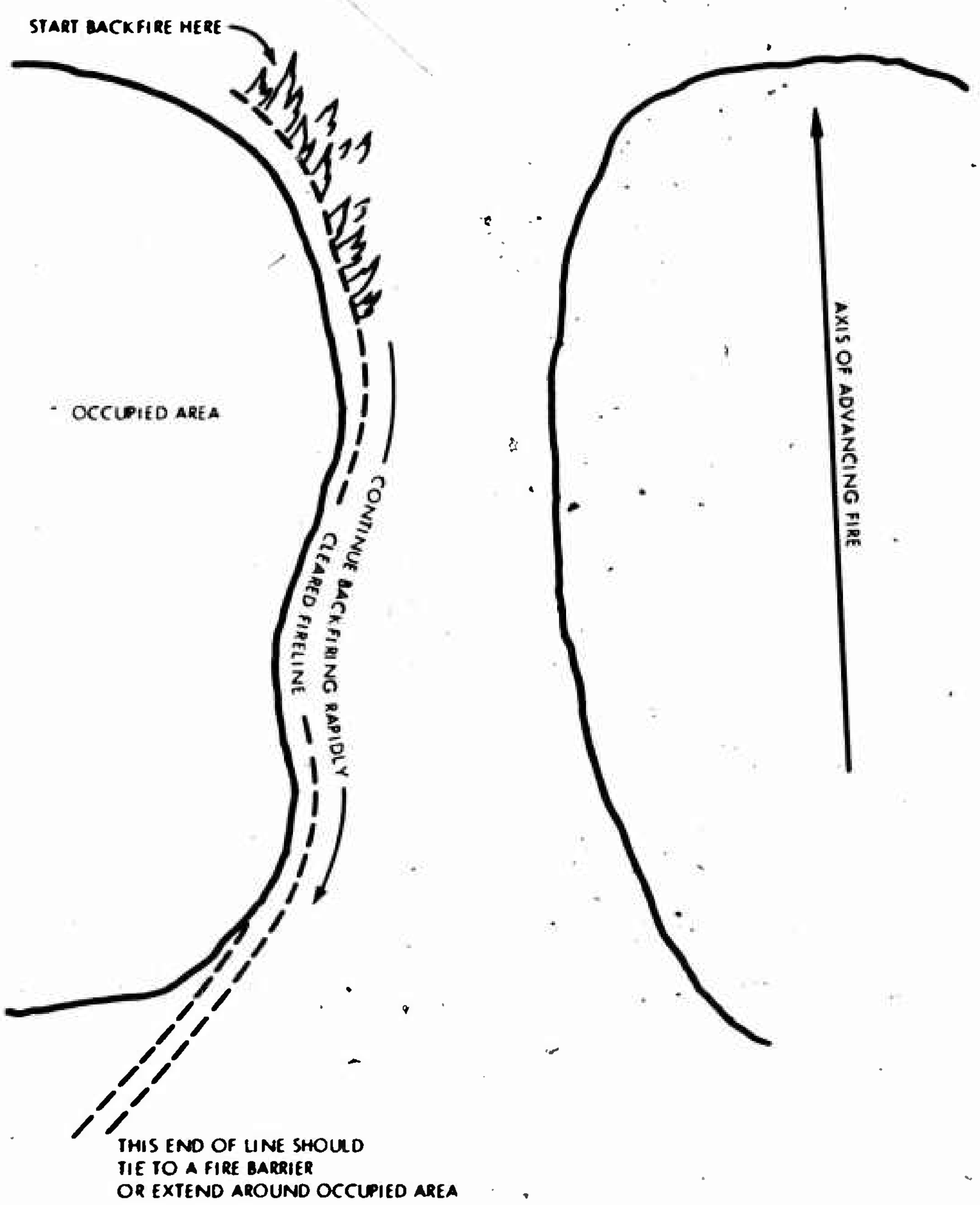

Figure 10-1. Fireline and backfiring procedure to protect an occupied area.

is assumed in this chapter that radiation monitoring is to be standing operating procedure.

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CHAPTER 11

FIRE DAMAGE AND EFFECTS

11.1 INTRODUCTION

Fires resulting from the employment of nuclear weapons over, within, or beneath forests or wildland areas may significantly affect communications, logistics, and tactical operations. These fires can overrun and destroy military units and related equipment, canalize forces, deny use of terrain, delay movement of ground combat forces, alter tactical operations by removing available cover and concealment, restrict movement of airmobile, mechanized, and armoured forces and cause partial blackout of short- and long-range radio communications and surveillance equipment.

11.2 FIRE TYPES

For military applications, fires can be classified into four distinct types, namely, ground fires, running surface fires, crown fires, and firestorms. Each of these fire types can affect military operations differently.

11.3 EFFECTS AND DAMAGE

11.3.1 Effects on Man and Materiel

Fires have a spectrum of effects against man and materiel. Where man is involved fire effects may vary from erythema (slight reddening of skin) to mass casualties due to varying degrees of burns or asphyxiation and edema from smoke and toxic gases. The spectrum of fire effects on materiel may include superficial scorching of wooden structures, blistering of surface paints or coating materials on ground combat equipment, buckling of vehicle, aircraft, and building structural components due to thermal loading, and total destruction by incineration.

11.3.2 Effects on Military Operations

Before proceeding with fire effects on military operations, two basic assumptions must be made. Units and related equipment immediately engulfed in an intense fire environment are largely destroyed unless well dug in. Those units and their equipment threatened by potential or approaching fire environments must elude or eliminate the fire threat in order to continue their mission.

Since it has been established that fires can produce mass casualties and equipment damage, the impact fires have on military operations will be restricted to protective and/or evasive techniques which may be employed in order for a unit to remain effective (i.e., capable of performing its mission). In order to determine the significance of fires on military operations it becomes necessary to evaluate the threat to combat forces for each particular fire type.

11.3.3 Creeping Surface Fires

Ground fires are characterized by slow burning at and below the surface of decomposed organic matter. This type of fire poses no significant threat to troops and mobile equipment in the combat zone. This type of fire usually spreads so slowly that there is sufficient time to initiate protective or evasive action. For equipment that is not easily moved or semi-permanent installations such as artillery batteries; petroleum, oil, and lubricant (POL) depots; ammunition storage and supply points; maintenance facilities; communications shelters, and command posts, the most effective protective measures would necessitate construction of fire lines around the perimeter of these installations. In order to afford these installations protection against the encroaching fire, these fire lines must penetrate into mineral soil. It should be noted that some organic soils often extend to great depths beneath the surface. Protection of the installation under these conditions involve large expenditures of manpower and equipment which are not always available to the commander in the field; therefore, when feasible, responsibility for fire control should be delegated to available combat engineer units.

Ground fires can leave the ground unstable since the organic soil has been reduced to ash; therefore movement in an area following a ground fire may be very difficult, especially if the organic soil is very deep. These factors must be considered by a commander before he makes the decision to employ protective or evasive measures against ground fires.

With respect to the disruption of radio communications and surveillance equipment, knowledge of the blackout regime associated with ground fires is limited. Blackout of communications and surveillance equipment is improbable in a ground fire environment; local interruptions of short duration are conceivable.

11.3.4 Running Surface Fires

Running surface fires are characterized by burning of surface litter, brush, and undergrowth. Fires of this type can alter military operations drastically. A commander whose unit is operating in an environment subject to a running surface fire has several options available to him. Once an estimate of the situation has been made, he may elect to fight the fire or evade it by withdrawing from its path and reoccupying the area after the fire has subsided. If he should decide to fight the fire, there are several fire control measures at his disposal. The most effective measures which the commander might employ include backfiring and construction of fire lines. These techniques and their limitations are discussed in Chapter 10. However, in certain vegetation types a unit and equipment may be able to penetrate the flank of the fire and occupy the burned area. The movement of troops and equipment into the burned area is limited by the fire intensity at the flanks, width of the fire flank, and vulnerability of man and equipment to residual heat in the burned-over area. Extreme caution must be used in moving equipment across the flanks of a running surface fire. Equipment which is most likely to present problems in crossing the fire flanks are rubber tired vehicles, tracked vehicles, and vehicles having easily ignitable canopies and covers. If the commander deems it necessary to evade the fire by withdrawal, he should determine the withdrawal route which represents the minimum risk to men and equipment. Guidance for withdrawal from an area threatened by fire is given in Chapter 10.

Those installations which are semi-permanent and/or located in rear echelons are subjected to a different fire threat than that confronting the ground combat units occupying forward areas. If there is insufficient time to remove the installations from the path of the fire, protective measures must be initiated. Once the decision has been made to protect these installations and not remove them, their survival depends on the effectiveness of the fire-control measures used. These fire-control measures include both backfire techniques and construction of fire lines. Fire lines should be constructed by utilizing all existing barriers (trails, roads, and streams) and supplementing these barriers with man-made fire lines. Once fire lines have been established around the perimeter of a facility, backfires may be necessary in order to contain the advancing surface fire.

11.3.5 Crown Fires

A crown fire, as its name implies, occurs within the crowns of trees and is characterized by intense burning and a rapidly moving front. Experience in fighting crown fires has shown that fire lines and backfires in the surface materials which support the crown fires are the most effective techniques for handling crown fires. Consequently, unit commanders who are confronted by crown fires and choose to fight the fire rather than take evasive action will find the most effective protective techniques (i.e., fire control measures) are the same as those used against running surface fires. He must realize, however, that his chances for successful control are considerably lessened.

Movement into a crown fire environment must be avoided because crown fires tend to be lethal to anything they engulf. Movement of those units threatened by crown fires will depend on the tactical situation, forest type, rate of fire movement, and wind speed. During crown fires it is possible for wind movement to cause smoke to settle to the ground, creating visibility problems which may hinder troop and vehicle movement. Units operating in the vicinity of crown fires should be prepared to encounter electronic blackout.

11.3.6 Firestorm

A firestorm is characterized by fire whirls of high intensity and relatively short duration as well as high winds due to massive updrafts of air. While personnel and materiel engulfed by a firestorm are invariably destroyed unless dug in below grade, it is not a primary threat to anyone operating at reasonable distances from the firestorm. The real threat to these troop units is due to ground, running surface, or crown fires which can generate radially from the firestorm. Therefore, the problems associated with military operations at some distance from a firestorm environment would be similar to the problems encountered in military operations near running surface and crown fire environments.

11.4 FIRE EFFECTS ON FALLOUT DISTRIBUTION

Radioactive fallout may be deposited on an area before, during, and after a fire. Since fires will alter fallout distribution, this becomes an operational problem. The amount of redistribution is dependent upon the type of fire and the meteorological conditions during the fire. In order to assess the radiological hazards of personnel and equipment operating near a particular fire environment or within a post-fire environment, constant radiological monitoring should be practiced.

11.5 FIRE EFFECTS ON VISIBILITY

The effects of ground fires, running surface fires, crown fires, and firestorms on visibility vary. Ground fires may smolder for many days and the amount of smoke produced has very little effect on visibility. Smoke from running surface fires can cause extremely limited visibility on the leeward side of the fire disrupting and delaying military operations. Usually crown fires do not present visibility problems since the smoke produced by them tends to rise upward and drift downward. High winds can cause smoke from crown fires to settle to the ground thus producing severe visibility problems. Smoke produced by firestorms should not affect surface visibility within operational distance since convection currents tend to cause smoke to rise upward and drift with the prevailing winds.

Operationally, smoke from fires is similar to chemical smoke in that it may act as a screening device and is not a significant threat to life except in the immediate fire environment. Smoke from fires differs from chemical smoke in that it can range to hundreds of square miles in the case of large forest fires.

11.6 POST-FIRE ENVIRONMENTS

The impact of a post-fire environment on military operations is dependent on the most damaging fire type incident upon the area and the degree of damage resulting. As a consequence, post-fire environments may alter military operations up to the limits listed in the following paragraphs.

11.6.1 Post-Fire Environments for All Fires

a. Unstable ground conditions may be created particularly in deep organic soil. This may create problems for movement of troops and equipment.

b. Fires may burn for many days underground in deep organic soils.

c. Following rain movement may be hindered by unstable footing and miring of vehicles and related equipment.

d. Horizontal concealment is decreased.

e. A layer of ash may cover the area; however this is not a significant hazard.

f. Wooden culverts, trestles, etc. are destroyed.

11.6.2 Post-Fire Environment for Crown Fires

a. In addition to the above effects, it radically decreases overhead concealment.

11.6.3 Post-Fire Environment for Firestorms

a. Along with the above effects, blown-down trees act as obstacles for troops and combat equipment.

11.7 SURVIVAL

A forest fire, as indicated earlier, presents an extremely hostile environment for both personnel and materiel. The first contributor to this adverse environment is heat output of the burning forest. In the pressure of flaming fuels, one frequently underrated consideration is that radiation accounts for about 25 percent of the total thermal heat output while convection contributes the far greater remainder. The second contributor to the adverse environment is the frequent combination of decreased oxygen supply, increased concentration of carbon dioxide, and the occasional presence of noxious carbon monoxide.

The mechanisms of radiant and convective heating and their consequent effects are quite different. Thermal radiation travels only in straight lines between its source and a potential receiver. It is also intercepted by any intervening opaque substance. Furthermore, the radiant energy received decreases with the square of the distance between source and receiver, and the rate of emission from forest fires is ordinarily low enough that significant time must elapse before the resulting temperature rise of the receiver becomes significant. Motion of the receiver with respect to the source, particularly turning to alternately present one side to the source while the opposite side cools, may largely negate the radiative effects.

Convective heating, on the other hand, is the transport of hot gases within and beyond the incandescent flame. This hot, turbulent flow may envelop and penetrate any body around and within which it may circulate, including man's respiratory system if he must inhale. When an object or person is involved in these hot gases the heat transfer is very rapid.

Normal field clothing is adequate in most cases for protecting all but exposed skin surfaces against radiant heating where uninhibited motion is possible. Aluminized outer fabric, including headgear, provides reasonably long term protection against this form of heating. Neither of these, however, provides adequate protection from flame, smoke, or hot gases. The respiratory tract is, of course, most vulnerable. One breath of flame is immediately lethal, and concentrated smoke and gases at far lower temperatures can be severely damaging. A gas mask, particularly one connected to a canister, will extend protection until heated beyond tolerance limits. A water-soaked hankerchief or other permeable fabric over the nose and mouth are next best. Ignition of clothing is an almost equal hazard. Additional layers of apparel, including a blanket or tarp that can quickly be discarded, are extremely helpful.

In the absence of physical obstructions, motorized transport through a flaming area is by far the safest mode. It may often be accomplished more quickly and perhaps of even more importance, passengers can retain a breath longer and breathe more shallowly when required. Over dependence on the supposed protection afforded by an unsealed cab is a frequent danger. A thermally unhardened vehicle may have to be sacrificed in such a traverse.

Once inside a flaming forested area, personnel safety is reasonably assured even though heat from residual glowing branchwood and logs may be intense. In this phase of combustion, radiant heat output is predominant. The principal heat sources are usually scattered, however, permitting moving personnel to thread their way between, in such a manner that constantly changing orientation and distance make these levels tolerable. Breathing is no longer a particularly serious problem.

11.8 CONCLUSIONS

Various types of fires are capable of destroying military equipment and producing casualties. If these fires are not controlled, they pose a significant threat to military units and equipment in their path. When a commander is confronted with a fire threat or contemplates the use of tactical nuclear weapons, he should consider the following factors before making a decision: mission, tactical situation, probable fire types, rate and direction of direction of fire movement, terrain, location of fallout areas, forest type, meteorological conditions, and the availability of fire fighting resources. After correlating these factors the commander's decision should reflect that course of action which facilitates accomplishment of the mission with the least risk to men and equipment.

Although fire behavior is not predictable enough to allow routine planning for its use as an effective weapon, it's potential can be exploited in special circumstances, particularly when it is unlikely to spread into the area of the user.

11.9 REFERENCES

1. Strom, P. and C. F. Miller. Interaction of Fallout with Fires, URS708-4, URS Researcn Co., San Mateo, California, September 1969.

2. Pryor, A., D. Johnson, and N. Jackson, Hazards of Smoke and Toxic Gases Produced in Urban Fires, Southwest Research, Inc., San Antonio, Texas, September 1969.

APPENDIX A

MASS FIRE DEFINITIONS

The following definitions have been prepared by Working Group J, Panel N-2, TTCP, and are to be used for TTCP communication on mass fire. When a deviation from these definitions is specifically required in a given case, such deviation will be pointed out and the meaning as used defined.

Radiant Exposure - The amount of radiant energy delivered on the area by the heat source. (As an example, for low altitude nuclear detonations, the express is:

$$Q = \int_0^{\infty} H dt \cong 2.6\, H_{max}\, t_{max} \text{ cal cm}^{-2}$$

where

H_{max} is the maximum irradiance

t_{max} is the time to maximum irradiance.)

Critical Radiant Exposure for Ignition - The radiant exposure from a nuclear weapon pulse at which 50 percent of a statistically valid sampling of specimens from the total population of a specific fuel or fuel-array ignite under specified test and assessment conditions. (To avoid ambiguity the radiant exposure should be specified in terms of H_{max} and t_{max}. Applicability is very sensitive to data spread about 50 percent point.)

Fuel-Size Categories -

1. Tinder: Combustible material of specific surface exceeding 20 square centimeters per gram or larger combustible materials having thermal conductivities less than 2×10^{-4} calories cm^{-2} sec^{-1} ($^{\circ}C$ cm^{-1}). May be ignited with a match.

2. Kindling: Combustible material of specific surface between 2 and 20 square centimeters per gram. Ignites and burns only when associated with sufficient tinder.

3. Bulk Fuel: Combustible material of specific surface less than 2 square centimeters per gram and a minimum of 1/2-inch thick.

Fuel Element - A flammable item of fuel, many of which taken together constitute a fuel unit.

Fuel Unit - In an urban area, a structure. In wildland areas, the smallest area containing a "typical" mix of fuels.

Fuel Array - An aggregation of tinder with or without kindling fuels oriented so as to be available for exposure to thermal radiation from nuclear detonations and possible ignition. (The critical radiant exposure, burning time and fuel content of the fuel array need to be specified for each fuel array in order to make a count of fuel arrays useful for estimating fire-start possibilities. Fuel arrays may be further subdivided into at least three groups with different probabilities of exposure, namely window fuel arrays, interior fuel arrays, and exterior fuel arrays.)

Ignition Point -

1. Location: The place in a fuel array where an ignition takes place whether or not ignition is sustained.

2. Temperature: The temperature at or above which a fuel surface exposed for a specific time and rate of heating will ignite and continue to burn in the absence of pilot ignition.

Incendiary Equivalent (Building Fires) - Amount of fuel capable of releasing 20,000 btu from an area of less than 1 square yard in 10 minutes or less. (Note that it is possible to translate fuel array, fuel content, and burning times into incendiary equivalents. If the summation of fuel values for fuel arrays with burning times of less than 10 minutes is divided by the area of the enclosure, the average "incendiary equivalent" load for the enclosure results.)

Firebrand - A flaming or glowing fuel element that is translated from its origin and is capable of starting another fire if it were to land in unburned fuel.

Flashover -

1. Building Fires: A usually readily recognizable endpoint to fire growth in a fuel array, at which point the entire array

reaches a threshold temperature and ignites almost simultaneously. (Can be quantified for specific cases in terms of surface heat loads in the array and/or transition to the process of ventilation control.)

2. Wildland Fires: Instantaneous ignition of accumulated unburned combustible gases.

Significant Fire - A fire which, if left alone, will fully involve the fuel array in which located. (Connotations for operations or for survival of people and/or resources are derivable.)

Uncontrollable Fire - A fire which can neither be halted nor extinguished with the means available, regardless of threat to population.

Controllable Fire - (Building Fires)

1. A fire that is not growing.

2. A fire that does not threaten population.

Fire Vortices -

1. Firewhirl: A transient spiral of elongated vertical flame formed within a fire area through convection action; analogous to "dust devils" in non-fire cases (Japanese - Tatsumaki).

2. Fire Tornado: A local fire-induced atmospheric storm exhibiting high-speed cyclonic motion and funnel form, which develops destructive force. The storm may remain in the fire-source area or move away from it.

3. Fire Cyclone: A very large firewhirl involving generalized circulation over an area fire. (May or may not form in a "firestorm.")

Area Fire - A region of fires having only minor ground interaction but combining to form a single convection plume; the plume is passive with little organization of vorticity. (Operationally, this marks the threshold of threat to major fractions of urban populations at risk.)

Group Fire - A number of individual fires burning within a readily definable external perimeter but which exhibit no radiative or convective interactions.

Mass Fire - A moving or stationary fire that has reached a size and rate of energy release such that further increase of area involved or of energy release rate will not significantly change fire behavior. Characterized by vigorous plume, generation or enhancement of vorticity, marked interaction of component fires: significant difference in thermal and aerodynamic characteristics, as compared to point or line heat sources.

Conflagration - A large destructive fire in which spread is primarily controlled by external influences such as wind or topography. Characterized by an essentially continuous fire front moving through a fuel bed; usually driven by ambient winds.

Firestorm -

1. A large destructive mass fire that develops from a large (not yet specifiable) number of starts in a large fuel bed during a period which is short in comparison with the violent burning time of the fuel units composing the bed. Characterized by a strong convection column and strong inflow winds at ground level which restrict spread out of the area of initial ignitions as well as by increases in intensity over time and sustained threats to population or other values.

2. A journalistic term applied to destructive wartime fires in Germany. By extension (challenged on scientific grounds), large urban fires that resemble those imperfectly described events. There is negligible evidence of discontinuous growth at a particular size, intensity, or wind inflow velocity.

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12. ABSTRACT

This handbook describes nuclear weapon thermal output and its effects on forest and wildland environments. Specific topics include a description of the nuclear thermal pulse and its transmission through the atmosphere for surface, atmospheric, and high-altitude bursts; ignition requirements of alpha cellulose and wildland fuels (including living vegetation); the classification and distribution of different types of forest fuels and climates and a discussion of fire potential, the behavior of single, multiple, and mass fires and firestorms; the post-fire environment, firefighting and evacuation methods; effects on military operations and man.

Also included for completeness are non-thermal effects on the forest and wildland — nuclear radiation and air blast effects — together with synergistic considerations, such as blast-fire and fire-fallout interactions.

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